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UNITED STATES
DEPARTMENT OF THE INTERIOR
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AIR VENT COMPUTATIONS
MORROW POINT DAM
COLORADO RIVER STORAGE PROJECT

Report No. HYD-584

HYDRAULICS BRANCH
DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

JULY 1968

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by

Dr. H. T. Falvey

July 1968

HYDRAULICS BRANCH
DIVISION OF RESEARCH

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Office of Chief Engineer . Denver, Colorado

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ABSTRACT

A computer program was written to determine the time-magnitude relationships of reduced pressures in the Morrow Point Dam inlet structure. The low pressures are formed during an emergency closure of the intake gates as water in the penstock drains through the turbine. The study was necessary to properly size the air vent system and to investigate the effect of various air vent dimensions on the reduced pressure. Consideration of design parameters, causes for air flow, and flow conditions within the air vent are discussed. The one-dimensional equations of gradually varying unsteady flow are given, and a computer program for their solution is presented in Fortran IV programming language. The program can be used for similar problems.

DESCRIPTORS--/ *vents/ *unsteady flow/ *air demand/ penstocks/ computer programming/ structures/ air/ velocity/ computation/ sound/ reservoirs/ design criteria/ mathematical analysis/ flow control/ adiabatic
IDENTIFIERS--/ Morrow Point Dam, Colo/ Colorado River Storage Proj/ Colorado/ water column separation

NOMENCLATURE

A = area, ft^2

C = discharge coefficient for compressible fluids

= Q actual/Q ideal

C_a = constant for atmospheric conditions of an isentropi flow process

C_D = discharge coefficient through emergency gate

D_f = friction loss factor

C_p = specific heat with pressure held constant

C_v = specific heat with volume held constant

C_{vel} = velocity coefficient for compressible fluids

= V actual/V ideal

D = conduit diameter, ft

H = length of water column in upper gate chamber under steady state conditions, ft

J = the mechanical equivalent of heat

= 778.16 ft lb_f/Btu

K = total energy loss factor

L = length, ft

M = Mach number = V air/V air sonic

$$= \frac{V}{\sqrt{g\,v\,kp}} = \frac{V}{\sqrt{g\,k\,R\,T_R}} \approx \frac{V}{49\sqrt{T_R}} \quad \text{(for air)}$$

M_i = ideal Mach number

Q = discharge, cfs

R = engineering gas constant

= 53.29 ft lb /lb °Rankine (for air)

T_R = temperature in degrees Rankine

= degrees Fahrenheit + 459.6

TW = tailrace water surface elevation

V = velocity, ft/sec

Vol = volume of air, ft^3

W = air mass, lb_m

WS = water surface elevation

Z = reference elevation

f = friction factor from a Moody diagram

g = gravitational constant

= 32.2 ft lb_m/lb_f sec^2

h_L = energy loss, ft

k = isentropic flow constant

= 1.4 for air

p = pressure, lb_f/in^2 for air

= pressure, lb_f/ft^2 for water

r = ratio of piezometric pressure in inlet region of air duct and stagnation pressure of atmosphere

= P_1/P_0

r_c = critical pressure ratio

s = Entropy

t = time, sec

v = specific volume of air, ft^3/lb_m

w = mass flow rate of air, lb_m/sec

y = distance between free water surface for steady state condition and free water surface at time t, ft

Subscripts

atm	=	atmospheric
c	=	compressible
e	=	location where Mach number = 1.0 for airflow
	=	entrance to small gate chamber for waterflow
g	=	emergency gate
GC	=	gate chamber
i	=	incompressible
p	=	penstock
R	=	reservoir side of gate chamber
res	=	reservoir upstream from bellmouth entrance
T	=	turbine
TW	=	tailrace
0,1,2,3	=	refer to Figure 11 for waterflow
	=	refer to Figure 12 for airflow

A bar over a value refers to an average value.

PURPOSE

The purpose of the study was to determine the magnitude of the reduced pressure in the Morrow Point Dam Powerplant intake gate structure as a function of time, to compute the maximum air velocities through the venting system, and to investigate the effect of the air vent dimensions on the reduced pressure in the penstock through the use of a digital computer program.

CONCLUSIONS

1. An individual 2-foot 9-inch by 3-foot air vent to each chamber prevents the pressure in the gate chamber and penstock from being less than 9.53 psia (pounds per square inch absolute) with an atmospheric pressure of 11.26 psi (pounds per square inch).

2. The maximum exit air velocity in the 2-foot 9-inch by 3-foot vent pipe is approximately 308 fps (feet per second).

3. The maximum inlet velocity 3 feet from the inlet to the 2-foot 9-inch by 3-foot air vent pipe is approximately 45 fps.

4. No water column separation occurs during the emergency closure.

APPLICATIONS

The analytical part of the study which is described by this report is complete. The computer program can be adapted for use on other geometrically similar installations by substituting appropriate values in all statements marked with an asterisk in the main program, in the subroutines, and in the function subprograms. If the other installations are not exactly geometrically similar, the program can still be used by rewriting the function subprograms. As with most mathematical models, the validity of curves presented in this report will not be definitely established until field tests have been performed. A time history of the gate chamber pressure and the percent gate opening during prototype operation would be sufficient to verify the accuracy of the computations presented in this report.

INTRODUCTION

Morrow Point Dam is one of three dams to be built on a 40-mile section of the Gunnison River in Colorado (Figure 1). The complex of dams, known as the Curecanti Unit, is primarily intended to develop water storage and hydroelectric power generation potentials on the river. Other purposes of the Unit are irrigation, recreation, and flood control.

The power generation facilities at Morrow Point Dam will consist of two generators whose combined capacity is about 120,000 kilowatts (Figures 2 and 3). The hydraulic structures associated with the generators are a single intake structure, two penstocks, two underground hydraulic turbine units, and their draft tubes (Figures 4 through 6).

Under normal operating conditions with flow through the turbines, the intake gates are fully open and water stands in the intake gate chamber (Figures 7A and 7B). The standard procedure for stopping the flow through the penstocks is to close the wicket gates at the turbine and then to close the intake gates. This procedure keeps the penstocks filled with water and eliminates difficulties which are normally experienced when the penstocks must be filled. However, during emergency conditions, the intake gates could close and the wicket gates at the turbine remain open. For this case, the water level in the gate chamber would fall rapidly and eventually all of the water in the penstock would be discharged through the runaway turbine (Figure 7C). This rapid change in the water surface decreases the air pressure in the gate chamber and in the penstock. The formation of excessive subatmospheric pressures in these structures is prevented by admission of air to the system through vents located in the intake structure.

This study was initiated to assist in the determination of the air vent size required at Morrow Point Dam. The procedure which is outlined can be applied to the solution of other similar air vent problems.

BASIC CONSIDERATIONS

A. Design Criteria

In general, the following factors must be considered in the design of air vent systems:

1. The limiting subatmospheric pressure which can be tolerated in the structure to which the air vent is attached.

2. The economy of constructing large air vents into a relatively weak connecting structure versus small air vents connected to a strongly reinforced structure.

3. The maximum air velocity which can be tolerated within the air vent duct.

4. The maximum air velocities at the entrance to the air vent duct.

5. The overall effect of the quantity of air flowing through the vents on the flow of water through the system.

Normally, a water conveyance structure, such as a penstock, is designed for the maximum positive internal pressure which might be encountered during the lifetime of its operation. Such a design is also safe against collapse up to some critical negative (below atmospheric) internal pressure. However, if the internal pressure could fall below this critical value, the structure must then be designed to resist both large positive and negative internal forces. In practice the magnitude of the negative internal pressures is often reduced by admitting air into the structure through a venting system. Thus, the requirement of designing the structure to resist large negative pressures can be avoided. However, to achieve significant reductions in the magnitude of the negative pressure, the vents may have to be quite large. Therefore, the designer must weigh the cost of a structure that can withstand excessive negative pressures versus the cost of providing large air vents into the structure. In some cases, the construction of a stronger structure may be more economical than providing for large air vents.

Consideration of the maximum air velocity in the vent pipes is dictated primarily from physiological considerations. The limit on the air velocities in the air vents has been established by experience at about 300 fps and is generally considered to be that air velocity at which an objectionable whistling sound occurs. The intensity of the sound and not the mere presence of sound is the governing factor. For instance, if the sound has pressure levels greater than about 85 db (decibles), ear protection is recommended for exposure times greater than 8 hours.1/ For pressure levels greater than about 135 db, ear protection is recommended for any exposure time. A relationship between air velocities and sound pressure levels in air vents cannot be given unless the air vent configuration is accurately known. However, various studies indicate that the sound pressure levels for certain types of noise increase as the 6th to 8th power of the velocity.2/ Therefore, the noise levels could quickly become objectionable if the 300-fps limit is exceeded. In addition to limiting the velocities within the vent, it is desirable to limit air velocities in the vicinity of the air intake to about 60 fps so that personnel and loose objects will not be swept through the vents. Personnel barriers, placing the intake in inaccessible locations, and grills or screens over the air intake are used to reduce this hazard.

1/Beranek, L. L., and Miller, L. N., The Anatomy of Noise, Machine Design, Vol 39, No. 21, September 1967.

2/Davies, H. G., and Williams, J.E.F., Aerodynamic Sound Generation in a Pipe, Journal of Fluid Mechanics, Vol 32, Part 4, pp 765-778, 1968.

The quantity of air flowing through the vents could adversely affect the flow conditions in the system under certain circumstances. For instance, insufficient air flow into the gate chamber could result in the formation of a vapor pocket in the penstock with subsequent separation of the water column. The rejoining of the water column would create extremely high pressures and could damage the penstock and gate chamber. Grigg, et al3/ have established that water column separation will not occur if the cross-sectional area of the flow passage in the lower part of the fully aerated gate chamber is greater than or equal to

$$\frac{Q_p}{\sqrt{2g(P/\gamma)_{atm}}}.$$

If this criterion is not met, computations of the type described in this report must be performed to determine if water column separation will occur.

B. Criteria for Airflow

The quantity of air which flows through the air vent is determined by both the configuration of the air vent and the flow conditions in the structure to which the vent is connected. Typical examples of flow conditions which may occur in the connecting structure are: the formation of a hydraulic jump which seals off the conduit, spray downstream from a gate, high-velocity flow in a partially filled conduit and a falling water surface. Each of these conditions is described by its own characteristic air-water flow relationship. Due to the variety of possible flow conditions, compressibility of the fluid flow through the air vent, and the design considerations enumerated previously, an air vent which satisfies the many requirements cannot be accurately designed through the use of simple "rules of thumb." Instead, the designer should use hydraulic model studies4/ or, in a few specialized instances, mathematical models.

Of the various flow conditions which were enumerated, the only air-water flow relationships that can be expressed mathematically are for

3/Grigg, W. L., Johnson, R. E., and Kellerhals, R., Some Design Aspects of a Divided Gate Tower, ASCE Proceedings, Vol 93, PO 2, pp 1-14, October 1967.

4/Sikora, A., Zavzdušnenie Šachtových Priepadov (Air Entrainment in Shaft Spillways), Práce a štúdie, 35, Výskumny Ustav Vodohospodarsky, Bratislava (Czechoslovakia). A presentation of dimensionless curves for high-velocity flow in a conduit flowing part full.

the hydraulic jump in a conduit5/ and for a falling water surface. Even though an explicit relationship cannot be obtained for a falling water surface in a complex structure, this report indicates a means by which the implicit relationships can be evaluated to approximate the true air-water flow relationship.

C. Description of Computational Procedures

1. Quasi-steady State Solution

The system could be analyzed in several different manners depending upon the rate of change of the waterflow rate. For instance, if the rate of change of the discharge is small enough, the assumption of quasi-steady flow is valid. For this case, the flow at the end of each time increment would be treated as though it had reached a steady state condition. The solution would involve the repeated application of Bernoulli's equation and the continuity equation. The air inflow rate has an influence on the pressure terms in Bernoulli's equation and simultaneously the continuity equation has an influence on the air inflow rate. Therefore, the solution involves a trial and error computation to arrive at the final result for each time increment.

2. Consideration of Inertial Effects

If inertial effects are not small, the system can be analyzed as a surge-type problem. In this type of problem, two equations based on conservation of momentum are written to describe the flow in the penstock and in the gate chamber, respectively. The relationship between the two equations is established through consideration of the energy equation at the point where the gate chamber flow joins the penstock flow. For some specialized cases, these two nonlinear second order differential equations can be combined into one equation which can be solved numerically.6/ However, since a numerical method is generally used for solving the equation, a simpler procedure is to solve the two differential equations simultaneously by standard Runge-Kutta numerical methods.7/8/ After the water drains out of the gate chamber, the flow can be described by one relatively simple second order differential equation.

5/Kalinske, A. A., and Robertson, J. M., Closed Conduit Flow, ASCE Transactions, Vol 108, pp 1435-1516, 1943.

6/Burgreen, D., Development of Flow in Tank Draining, ASCE Proceedings, HY3, pp 13-28, March 1960.

7/Scarborough, J. B., Numerical Mathematical Analysis, John Hopkins Press, 1966.

8/Willers, F. A., Practical Analysis, Dover Publications, 5273, 1948.

This type of computation generally falls under the heading of "Rigid Water Column Theory" and forms the basis for the computations described in this report.

3. Consideration of Compressibility Effects in the Water Columns

The previous method assumes that the water column is incompressible, which means pressure changes due to closure of the emergency gate are transmitted throughout the entire system instantaneously. Parmakian9/ states that this assumption is satisfactory when the gate closure time, T, is greater than L/1,000, where L is the length of the water column. If T is less than L/1,000, the effects of compressibility of the water column should be included in the analysis. The analysis which considers compressibility effects is known as "Elastic Water Column Theory." The mathematics is made more complex than the previous methods through the introduction of partial differential equations. Therefore, an examination of the necessity for considering an elastic water column can lead to simplifications in the analysis.

The Morrow Point Dam penstock is about 470 feet long, and the total gate closing time was assumed to be 60 seconds. Thus, T is about 120 times greater than L/1,000 and the effects of compressibility in the water columns can be safely neglected.

D. Deviations from the Prototype

Various discrepancies frequently occur between a mathematical model and the prototype because of simplifying assumptions made in the mathematical model. If these deviations from actual conditions are minor, the mathematical model can still be expected to yield accurate results.

The simplifying assumptions used in the method of analysis described by this report which could cause discrepancies are:

a. Flow into the gate chamber along the upstream face of the partially open emergency gate is neglected.

b. The emergency gate closing rate is constant.

c. The loss coefficient across the turbine is constant.

The effect of these deviations was assumed to be minor. The validity of this assumption should be confirmed by prototype tests.

9/Parmakian, J., Water Hammer Analysis, Dover Publications, New York, 1963.

THE COMPUTER PROGRAM

A. General

The computer program determines quantities which satisfy the rigid water column flow equations. A general outline of the steps which the computer performs is shown in the flow chart (Figure 8). Basically, the program consists of two computational loops. The purpose of the major loop is to solve the two second-order, nonlinear differential equations simultaneously. Within the major loop, a secondary loop determines the airflow quantities through the vents. The program begins at the time corresponding to the inception of the emergency gate closure, computes the flow quantities for this time, increases the time by a fixed time increment and then repeats the computations. This procedure is continued until some preestablished time from inception of the gate closure has been reached. Then the program stops the computations. Only the major divisions of the program are discussed in the headings which follow, since details of the actual steps can be obtained from an examination of the program itself (written in FORTRAN), see Appendix.

B. Numerical Integration

The numerical integration is performed by the computer using the Runge-Kutta method in combination with "smoothing" or corrector equations. The Runge-Kutta method is actually a family of procedures for solving differential equations in which each procedure has its own characteristic degree of accuracy.10/ The particular method used in this report consists of the following procedure (refer to Figure 9A):

> The first approximation of the differential equation is a straight line whose slope is determined at the starting point.
>
> The second approximation is a straight line passing through the starting point but whose slope is determined at the midpoint of the first approximation.
>
> The slope for the third approximation is determined at the midpoint of the second approximation.
>
> Finally, the slope of the fourth approximation is determined at the end point of the third approximation.

These four approximations result in four values of the differential equation at the end of the time interval, Δt , where Δt is the time increment used in the integration. An average value is obtained by using Simpsons rule.10/ The inherent error with this method is of the order $\Delta t5$.

10/Streeter, V., and Wylie, E. B., Hydraulic Transients, McGraw-Hill Book Company, 1967.

The simultaneous solution of two differential equations, g_1 and g_2, can be considered geometrically as the determination of a solution curve in three-dimensional space with coordinates x, y, and t (Figure 9B). The Runge-Kutta method of integration for this three-dimensional case is similar to that for the two-dimensional case described by one differential equation. At the end of the time interval Δt, values of both Δx and Δy are determined for the two differential equations.

To insure the accuracy of the integration, short-time intervals were used. The values of x, y, v_x and v_y computed by the Runge-Kutta method were checked and corrected by assuming that the second-order time-derivatives could be expanded with a five-term Taylor series. For example, in this program the basic time increment for which values were desired was 1.0 second. To perform the integration this interval was broken into five equal intervals and the integration was performed using the Runge-Kutta method for each interval giving five values of x, y, v_x and v_y. These values were then corrected using standard corrector equations which are based on a five-term Taylor series.11/ A forward integration technique was used to extend the computations from the fifth value (the end of the fourth interval) to the end of the 1.0-second interval. This procedure resulted in water velocities which were correct to four places.

At the end of each time increment, the airflow rate through the vents is computed by solving simultaneously the compressible fluid flow equations for the airflow with the equation for the adiabatic expansion of air in the gate chamber. Although this computation changes the value of the pressure above the water surface in the gate chamber, the use of small time increments and the relatively slow rate of change of gate chamber pressure eliminates the need for repeating the integration.

C. Computation of Discharge Coefficient

The discharge coefficient for the intake gate is a function of both the gate opening and of the downstream conditions. If the water surface downstream from the gate is high enough to effect the discharge coefficient, the efflux is termed "submerged." For lesser water depths, the efflux is called "free." Unfortunately, the effect of submergence on the discharge coefficient of a slide gate located immediately downstream from the end of a bellmouth entrance is not presently available. Therefore, the discharge coefficients for a freely discharging slide gate were used in the program.12/ The discharge coefficient curve was approximated with a fifth degree polynomial using a least squares fit (Figure 10).

11/Levy, H., and Baggott, E. A., Numerical Solutions of Differential Equations, Dover Publications, S168, 1950.

12/Falvey, H. T., Twin Buttes Auxiliary Regulating Gate, Report No. HYD-475, United States Bureau of Reclamation, Denver, Colorado.

The differential head across the gate was used to computed the discharge for the submerged condition. Whereas, the upstream head was used for the free-flow condition.

The emergency gate was assumed to have a linear rate of closure, going from wide open to fully closed in 1 minute. Thus, for each time interval, the percent gate opening was defined. The discharge coefficient which corresponded to a given gate opening was obtained from the polynomial expansion.

D. Computation of the Gate Chamber Pressure

As the water surface drops, the air in the gate chamber and penstock will expand adiabatically. This results in a decrease of the gate chamber pressure. The decreased gate chamber pressure in turn will increase the airflow rates through the air vents. The increased amount of air in the chamber will partially relieve the low pressure. This portion of the program was repeated until the pressure which created a certain airflow rate equaled the pressure formed by the adiabatic expansion of the previous air volume and of the air volume which flowed through the air vent.

E. Computation of the Mach Numbers in the Air Vent

Part of the computation of the gate chamber pressure involved computation of the airflow rate through the vent. Because the flow in the air vent is compressible, the Mach number of the flow into the vent is less than the Mach number of the flow out of the vent. The computer program computed the outlet Mach number based on a given value of the inlet Mach number. The inlet Mach number was determined from the airflow rate required to satisfy the gate chamber pressure.

F. Restrictions Imposed on the Computations

Since the flow equations were solved through successive approximations, maximum allowable error limits were imposed on the required accuracy of specific computations. These limits were as follows:

1. The pressure of the air in the gate chamber or penstock must be correct to with 0.01 psi of its true value.

2. The Mach number of the air entering the gate chamber must be with 0.1 percent of its true value as determined by the compressible flow equations.

These error limits result in a solution which converges rapidly. Smaller increments for the various steps increase the computation time but do not significantly change the absolute values of the flow quantities. Therefore, these limits can be considered as an optimization of the required computational accuracy for a minimum computation time.

In addition to these restrictions, the computations will cease if vapor pressure is reached in the system since this is a condition which is not defined by the differential equations. Then too, the structure could be endangered if vapor pressures did form in the water columns.

To insure a unique solution at the very low airflow rates, the specific weight of the air in the gate chamber must be equal to or less than the specific weight of air at atmospheric pressure.

DEFINITION OF BASIC EQUATIONS

A. Discharge from Reservoir into Penstock

The flow rate from the reservoir into the penstock is a function of the reservoir elevation, the gate opening, and the pressure downstream from the gate. These quantities were related through the expression:

$$Q_R = A_g C_D \sqrt{2g} \sqrt{WS_{res} - Z_p - P_R/\gamma} \qquad (1a)$$

for submerged flow and

$$Q_R = A_g C_D \sqrt{2g} \sqrt{WS_{res} - Z_p + P_{GC}/\gamma - P_{atm}/\gamma} \qquad (1b)$$

for free flow in the penstock

For these computations, a constant reservoir elevation of 7165.0 was assumed. The conduit invert elevation is 7073.25 and the conduit area at the upstream face of the gate is 222.13 square feet (13.52 x 16.43). The discharge coefficients were defined by a fifth degree polynomial which approximated the discharge curve, Figure 10.

B. Momentum Equation for Gate Chamber Flow

The gate chamber configuration was simplified by assuming that it consisted of two main parts, one having a large cross-sectional area and the other small (Figure 11). Equating the body forces and the gravitational forces on the water in the upper gate chamber with the inertia of the fluid gave:

$$P_oA_1 - P_1A_1 + \gamma(H - y_1)A_1 = \frac{\gamma(H - y_1)}{g} A_1 \frac{d^2y_1}{dt^2} \tag{2}$$

Similarly equating body forces, gravitational forces, entrance drag forces and frictional forces in the lower gate chamber with the inertia of the fluid gave:

$$P_2A_2 - P_3A_2 + \gamma L_2A_2 - \frac{\gamma}{2g} A_2\left(\frac{fL}{D} + K_e\right)\left(\frac{dy_2}{dt}\right)^2$$

$$= \frac{\gamma L_2}{g} A_2 \frac{d^2y_2}{dt^2} \tag{3}$$

Equations 1 and 2 are related to each other through the energy equation written at the junction of the upper and lower gate chambers:

$$\frac{\gamma}{2g}\left(\frac{dy_1}{dt}\right)^2 + P_1 = \frac{\gamma}{2g}\left(\frac{dy_2}{dt}\right)^2 + P_2 \tag{4}$$

Through the continuity equation:

$$A_1y_1 = A_2y_2 \tag{5}$$

Equations 2 through 4 can be combined into one equation which describes the flow out of the gate chamber:

$$\frac{P_o}{\gamma} - \frac{P_3}{\gamma} + (H - y_1 + L_2) - \frac{1}{2g}\left[\left(1 + \frac{fL}{D} + K_e\right)\left(\frac{A_1}{A_2}\right)^2\right.$$

$$\left. - 1\right]\left(\frac{dy_1}{dt}\right)^2 = \frac{1}{g}\left[H - y_1 + L_2\left(\frac{A_1}{A_2}\right)\right]\frac{d^2y_1}{dt^2} \tag{6}$$

If the water surface is in the lower gate chamber, the equation which corresponds with Equation 6 is:

$$\frac{A_1(L_2+H-y_2)}{A_3\ g}\frac{d^2y_2}{dt^2}=\frac{P_o}{\gamma}-\frac{P_3}{\gamma}+(L_2+H-y_2)$$

$$-\frac{fL}{D}\left(\frac{A_1}{A_3}\right)^2\frac{1}{2g}\left(\frac{dy_2}{dt}\right)^2 \qquad (7)$$

C. Momentum Equation for Penstock Flow

The momentum equation for the penstock flow can be written by equating body, frictional, and gravitational forces with inertia. This gives:

$$\frac{P_p-P_4}{\gamma}+Z_p-Z_{TW}-\frac{fL_p}{D}\frac{1}{2g}\left(\frac{dx}{dt}\right)^2=\frac{L_p}{g}\frac{d^2x}{dt^2} \qquad (8)$$

The pressure at the end of the penstock, P_4, can be expressed in terms of the tailrace water elevation through the Energy Equation:

$$\frac{1}{2g}\left(\frac{dx}{dt}\right)^2+\frac{P_4}{\gamma}=\frac{K_T}{2g}\left(\frac{dx}{dt}\right)^2+TW-Z_{TW} \qquad (9)$$

The value for K_t is determined from the steady state conditions of flow through a runaway turbine. It is assumed that K_t is not a function of head across the turbine. For Morrow Point Dam, a maximum discharge of 5,530 cfs with a 405-foot head was used to compute K_t for the runaway condition. In Equation 9, the velocity head in the tailrace was neglected.

Substitution of P_4 from Equation 9 into Equation 8 yields the penstock momentum equation:

$$\frac{P_p}{\gamma}-\frac{K_T-1}{2g}\left(\frac{dx}{dt}\right)^2-TW+Z_p-\frac{fL_p}{2g\,D_p}\left(\frac{dx}{dt}\right)^2=\frac{L_p}{g}\frac{d^2x}{dt^2} \qquad (10)$$

If the free water surface is in the penstock, the length L_p is the length of the water column in the penstock between the free water surface and the turbine.

D. Junction Energy Equations

The equation for the reservoir flow (Equation 1), the equation for the gate chamber flow (Equation 6 or Equation 7), and the penstock flow equation (Equation 10) are all related to each other through energy considerations at the junction of the gate chamber with the penstock.

The distribution of energy at a pipe branch or tee has been investigated by several researchers.13/14/ The results of analytical computations were found to agree relatively well with experimental data. If the water enters the penstock from both the gate chamber and from the reservoir, the approximate relationship between the pressure immediately below the emergency gate and the penstock pressure is:

$$\frac{P_R}{\gamma} = \frac{V_p^2}{2g} + \frac{P_p}{\gamma} - \frac{V_R^2}{2g} + h_L \qquad (11)$$

where

$$h_L = \left[1 - \left(\frac{Q_R}{Q_p}\right)^2\right] \frac{V_p^2}{2g}$$

Similarly, the pressure in the gate chamber can be expressed by:

$$\frac{P_3}{\gamma} = \frac{P_p}{\gamma} + \frac{V_p^2}{2g} - \frac{V_3^2}{2g} - D_p + h_L \qquad (12)$$

where

$$h_L = \left[4\,\frac{Q_{GC}}{Q_p} - 1 - \left(2 - \frac{A_p^2}{A_3^2}\right)\left(\frac{Q_{GC}}{Q_p}\right)^2\right] \frac{V_p^2}{2g}$$

13/Blaisdell, F. W., Loss of Energy at Sharp-edged Pipe Junctions, Technical Bulletin No. 1283, Agricultural Research Service, USDA, 1963.

14/Gardel, A., Chambers D'Equilibre, F. Rouge and Cie, Lausanne, 1956, see also Perkins, F. E. et al, 1964, Hydro Power Plant Transients, Part III, Hydrodynamics Laboratory Report No. 71, Massachusetts Institute of Technology.

With free surface flow in the penstock the head loss across the junction is zero, as can be seen from Equation 11 when $Q_R = Q_p$.

E. Initial Conditions for the Differential Equations

To start the integration of Equations 6 and 10 certain initial conditions must be given. These conditions can be obtained by solving Equations 6 and 10 for the steady state condition ($d^2x/dt^2 = 0$ and $d^2y/dt^2 = 0$). Thus at time, t = o, the initial conditions are:

$$x = 0; \quad dx/dt = 17.776 \text{ ft/sec}$$

$$y = 0; \quad dy/dt = 0$$

The initial conditions for Equation 7 were obtained by assuming conservation of momentum in the gate chamber and in the penstock as the flow left the upper gate chamber. This assumption makes dx/dt and dy/dt continuous functions. In this case dy/dt must be referenced to the lower gate chamber.

F. Compressible Fluid Flow in the Air Vents

1. General - The differential equation of motion for compressible flow in a constant area duct when losses are considered is:

$$\frac{dp}{p} + \frac{\gamma}{2} dM^2 + \frac{\gamma}{2} M^2 \frac{dT}{T} + \frac{dD_i}{pA} + \frac{\gamma}{2} \frac{M^2 f}{D} dx = 0 \qquad (13)$$

(Ref. 15/, p 93.)

This equation can be solved if the flow is considered as being described by two separate flow regimes, an inlet flow regime and a duct flow regime (Figure 12A). For the inlet regime, the losses are primarily dependent upon form drag, and the effect of friction is neglected. In the duct regime, the losses are caused primarily by friction drag. Thus, the general differential equation is reduced to the following two simple differential equations:

With friction drag = 0,

$$\frac{dp}{p} + \frac{\gamma}{2} dM^2 + \frac{\gamma}{2} M^2 \frac{dT}{T} + \frac{dD_i}{pA} = 0 \qquad (14)$$

15/Hall, N. A., Thermodynamics of Fluid Flow, Prentice Hall, New Jersey, 1956.

With the form drag = 0,

$$\frac{dp}{p} + \frac{\gamma}{2} dM^2 + \frac{\gamma}{2} M^2 \frac{dT}{T} + \frac{\gamma}{2} \frac{M^2 f}{D} dx = 0 \qquad (15)$$

The solutions to these equations can be found in standard thermodynamic textbooks.15/16/17/ The most pertinent solutions using these equations are summarized and discussed in the following sections.

The solution of either equation is based on adiabatic (no heat transferred) flow in the air vent because both the length of the vents and the flow durations are short. Therefore, the amount of heat transfer which can take place is insignificant when compared with changes in air temperature. In addition, the air is assumed to obey the perfect or ideal gas laws. This means that the factor k , in the equation,

$$pv^k = \text{constant} \qquad (16)$$

remains constant. Actually, the factor k is a function of both temperature and pressure. However, for the temperature and pressure ranges which are experienced with air vent flows, the value of the factor is essentially constant.

2. Inlet flow - Computations of flow quantities in the inlet flow regime can be carried out in two distinct ways. First, the inlet flow regime can be considered as consisting of an accelerating zone followed by a decelerating zone, Figure 12A. The flow in the accelerating zone is characterized by varying area adiabatic flow with no change in entropy. The decelerating zone is characterized by constant area adiabatic flow in which changes in entropy are determined by integration of Equation 14. The drag term D_1 is defined as:

$$D_1 = \frac{K}{2} P_2 M_2^2 C_d A_2 \qquad (17)$$

To integrate the equation, an expression giving the drag coefficient, C_d, as a function of the Mach number is required. Often C_d is

16/Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol I, the Ronald Press, New York, 1953.

17/Obert, E. F., and R. A. Gaggioli, Thermodynamics, 2nd Ed, McGraw-Hill, New York, 1963.

assumed to be independent of the Mach number and is given the same value as it has with uncompressible flow (Ref. 15/, p 48). However, the validity of this assumption is somewhat questionable.

A second and probably the most accurate way of determining the inlet flow relations is to consider the entire region as being varying area adiabatic flow (Ref. 15/, p 120). The energy losses (or increases in entropy) are expressed through discharge and velocity coefficients which are determined experimentally.

Starting with an ideal discharge Mach number (no loss) at the end of the inlet region, the pressure ratio between the inlet and the stagnation pressure outside of the inlet is:

$$r = \frac{P_1}{P_o} = \left(1 + \frac{K-1}{2} M_{11}^2\right)^{-\frac{k}{k-1}} \tag{18}$$

With this pressure ratio, the compressible flow discharge coefficient can be obtained (Ref. 16/, p 100; Ref. 17/, p 337; and Ref. 18/).

For this computation, the equation:

$$\frac{1-C}{1-C_{inc}} = 1 - 0.7(C_{inc} - 0.1)\,\frac{\left(\frac{1}{r} - 1\right)}{\left(\frac{1}{r_c} - 1\right)} \tag{19}$$

from Reference 18 is probably the most useful. This expression is an empirical relationship in which the compressible discharge coefficient is computed from an experimentally determined value of the incompressible discharge coefficient. Equation 19 is valid for pressure ratios less than the critical pressure ratio:

$$r_c = \frac{P_1}{P_o} = \left(\frac{K-1}{2}\right)^{-\frac{k}{k-1}} \tag{20}$$

18/Annand, W.J.D., Compressible Flow through Square-edged Orifices; An Empincal Approximation for Computer Calculations, Journal Mechanical Engineering Science, Vol 8, No. 4, pp 448-449, 1966.

For larger ratios the following empirical relationship must be used to determine the compressible discharge coefficient:

$$\frac{1 - C}{1 - C_{inc}} = 1 - 0.7(C_{inc} - 0.1) - (0.27 + 0.1\ C_{inc})$$

$$\left[1 - \left(\frac{r}{r_c}\right)^2\right] \tag{21}$$

When the compressible discharge coefficient has been determined, the true Mach number at the end of the inlet section can be obtained from:

$$C = \frac{M_1}{M_{1i}}\left[\frac{1 + \frac{K-1}{2} M_1^2}{1 + \frac{K-1}{2} M_{1i}^2}\right]^{\frac{1}{2}} \tag{22}$$

The velocity coefficient is given by:

$$C_{vel} = \frac{M_1^2}{C\ M_{1i}^2} \tag{23}$$

From this the velocity at Point 1 is given by:

$$V_1 = C_{vel}\sqrt{\frac{2kg\ RT_o}{k - 1}\left[1 - \left(\frac{P_1}{P_o}\right)^{\frac{k-1}{k}}\right]} \tag{24}$$

All of these relationships are required to compute the increase in entropy through the inlet region from the expression:

$$e^{-\frac{\Delta s}{R/J}} = \left(\frac{C}{C_{vel}}\right)^{\frac{k}{k-1}} \tag{25a}$$

With no external work, the entropy expression is also equal to the ratio of the stagnation pressures downstream and upstream from the intake. Thus:

$$\frac{P_1}{P_o} = e^{-\frac{\Delta s}{R/J}} \tag{25b}$$

Finally the mass flow rate through the inlet in terms of the true Mach number at the end of the inlet region is:

$$w = \frac{P_o A}{\sqrt{\frac{RT_o}{kg}}} e^{-\frac{\Delta s}{R/J}} \frac{M_1}{\left(1 + \frac{K-1}{2} M_1^2\right)^{\frac{k+1}{2(k-1)}}} \tag{26}$$

The various flow relationships expressed by Equations 18 through 26 are given in Figure 12B. The mass flow rate is shown for a vent area of 8.25 ft^2 (2.75 ft x 3.0 ft) and air temperatures of 40° and 60° F. The 40° F curves were used in the computer program. A program to compute the values of Equations 18 through 26 is given in the Appendix.

3. Duct flow - The flow conditions in the remainder of the air vent are described by the equation for adiabatic flow in a constant area cross section in which the losses are caused by friction, Equation 15. The complete set of equations describing flow in this region are generally referred to as the Fanno Equations after an early investigator in this field. The effect of bends, changes in cross-sectional area, and other types of form losses can be simulated by expressing them in an equivalent length of air vent pipe. In this manner, an overall or equivalent friction coefficient for the air vent is obtained. The friction coefficient is defined as:

$$C_f = \frac{\bar{f}L}{D} \tag{27}$$

Tables of the flow properties are available for the Fanno Flow relationships in which the inlet Mach number is the variable and the outlet Mach number is equal to 1.0.15/16/17/ The tables are based on the following equations; the pressure at the end of the duct in terms of the pressure at "1" is given by:

$$\frac{P_1}{P_e} = \frac{1}{M_1}\left[\frac{K+1}{2\left(1+\frac{K-1}{2}M_1^2\right)}\right]^{\frac{1}{2}} \tag{28}$$

the friction factor is given by:

$$\frac{fL_{max}}{D} = \frac{1-M_1^2}{KM_1^2} + \frac{K+1}{2K}\,\ell n\left[\frac{(K+1)\,M_1^2}{2\left(1+\frac{K-1}{2}M_1^2\right)}\right] \tag{29}$$

The pressure ratio, at the duct exit when the Mach number M_2 is not equal to 1.0, is given by:

$$\frac{P_1}{P_2} = \left(\frac{P_1}{P_e}\right)_{M_1} \cdot \left(\frac{P_e}{P_2}\right)_{M_2} \tag{30}$$

The corresponding friction factor is given by:

$$\frac{fL}{D} = \left(\frac{fL_{max}}{D}\right)_{M_1} - \left(\frac{fL_{max}}{D}\right)_{M_2} \tag{31}$$

4. Critical pressure ratio - Both experiments and the flow equations indicate that the flow rate reaches a maximum value for some given ratio of the inlet to outlet pressures. This ratio is known as the "critical pressure ratio." If the outlet pressure is decreased after the critical pressures ratio is reached, the flow rate does not increase, but remains constant. When the critical pressure ratio is obtained, then somewhere in the air vent a Mach number equal to unity (or a shock wave) has developed. At the critical pressure ratio with inlet flow, the shock wave forms at the location of the vena contracta. If however, a length of duct is placed downstream from the inlet and the critical

pressure ratio is maintained, then the shock wave can form at the exit of the duct instead of at the vena contracta.

For ideal flow through a frictionless nozzle, the value of the critical pressure ratio is 0.5283. However, the value of the critical pressure ratio is less than 0.5283 when friction losses or inlet losses are significant. The critical pressure ratio considering only friction losses for a specific Mach number at "1" can be obtained from Equations 20 and 28 using the relationship:

$$\frac{P_e}{P_o} = \frac{P_1}{P_o} \cdot \frac{P_e}{P_1} \tag{32}$$

The friction coefficient which corresponds to the specified Mach number at "1" is given by Equation 29.

If both friction and inlet losses are to be considered, then Equations 25b and 28 must be used in conjunction with Equation 32.

The critical pressure ratios with and without inlet loss for various lengths of air vent conduits are shown in Figure 13. The values given represent a shock wave forming at the end of the air vent. The asymptotic lines (dashed lines on the ordinate) represent a shock wave in the vena contracta of the inlet region. The curves are referenced to both the downstream stagnation pressure and the pressure at the duct exit. Normally the critical pressure ratio is referenced to the pressure at the duct exit and the inlet stagnation pressure.

G. <u>Adiabatic Expansion in Gate Chamber</u>

The adiabatic expansion of air in the gate chamber is based upon:

$$pv^{1.4} = C_a \tag{33}$$

The specific air volumn, v , is computed for each time increment from the equation:

$$v_{t+\Delta t} = \frac{Vol_{t+\Delta t}}{W_t + \Delta w} \tag{34}$$

where

$Vol_{t+\Delta t}$ = air volume at end of time increment

W_t = mass of air at beginning of increment

$$\Delta W = \frac{(w_t + w_{t+\Delta t})\,\Delta t}{2}$$

= change in air mass during time interval from time = t to $t+\Delta t$

w = mass flow rate through the air vent

The constant, C_a , in Equation 33 is computed from known atmospheric conditions in the gate chamber at the steady state condition before the gate begins closing.

H. Gate Chamber and Penstock Volumes as a Function of Elevation

The air volume of the gate chamber and the penstock above any water surface elevation is a function of elevation. This function is a complicated algebraic expression. Therefore, to simplify the computation, the complicated expression is replaced with four linear equations. A plot of the volume as a function of elevation is given in Figure 14.

RESULTS OF COMPUTATIONS

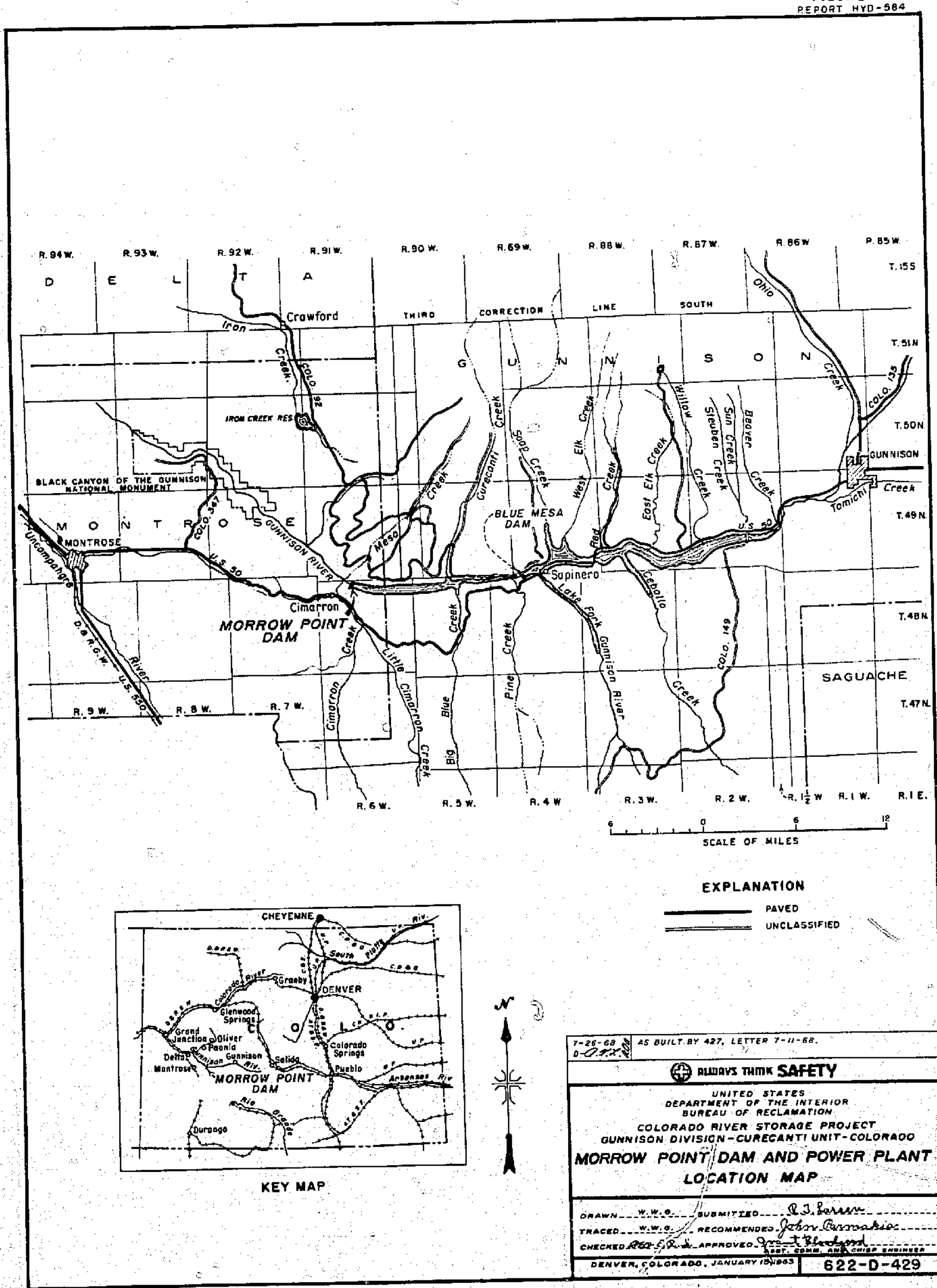
The air vent configuration which was used in the final design consisted of a separate 2-foot 9-inch by 3-foot air vent to each gate chamber. With this design the maximum pressure drop in the gate chamber is 1.73 psi or 3.99 feet of water below atmospheric pressure, Figure 15A.

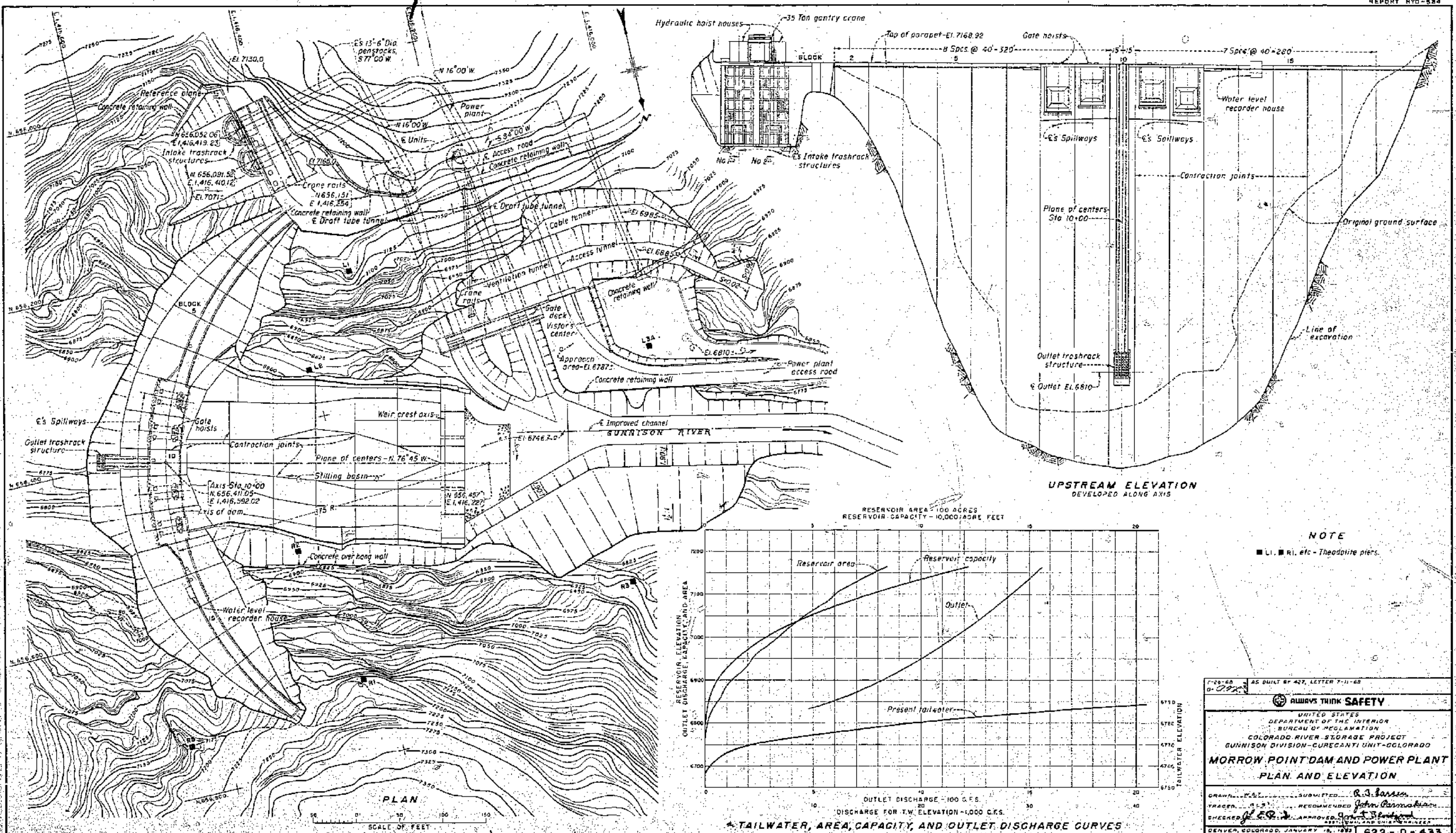
The maximum air velocity in the vent is 308 fps, Figure 15B. Assuming that the air flow approaches only from in front of the air vent, an air velocity of 101 fps will result at a point 2 feet distant from the air vent intake. At 3 feet, the air velocity is reduced to 45 fps. Therefore, personnel should be prevented from approaching nearer than about 4 feet from the intake to the air vent.

The minimum pressure in the penstock and gate chamber does not drop below the vapor pressure of the water, Figure 15C. Therefore, separation of the water column will not occur.

From the standpoints of pressure drop in the gate chamber, maximum air velocity, and flow conditions in the penstock, the air vent, as designed, is completely satisfactory.

FIGURE 1
REPORT HYD-584





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BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
GUNNISON DIVISION-CURECANTI UNIT-COLORADO

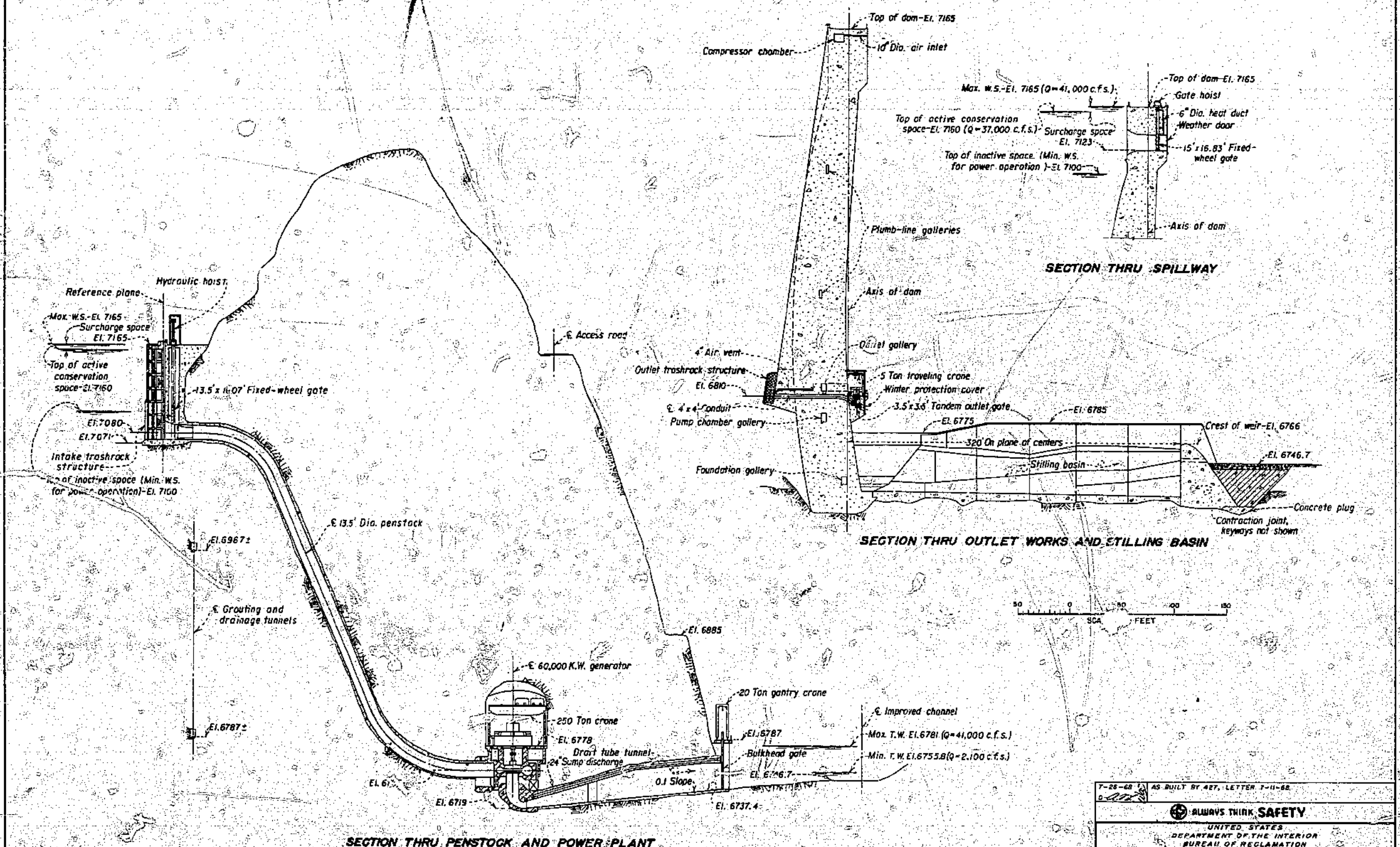
MORROW POINT DAM AND POWER PLANT
PLAN AND ELEVATION

AS BUILT BY 427, LETTER 7-11-68

DENVER, COLORADO, JANUARY 16, 1963

622-D-433

FIGURE 3
REPORT HYD-584



7-26-68 AS BUILT BY 427, LETTER 7-11-68.

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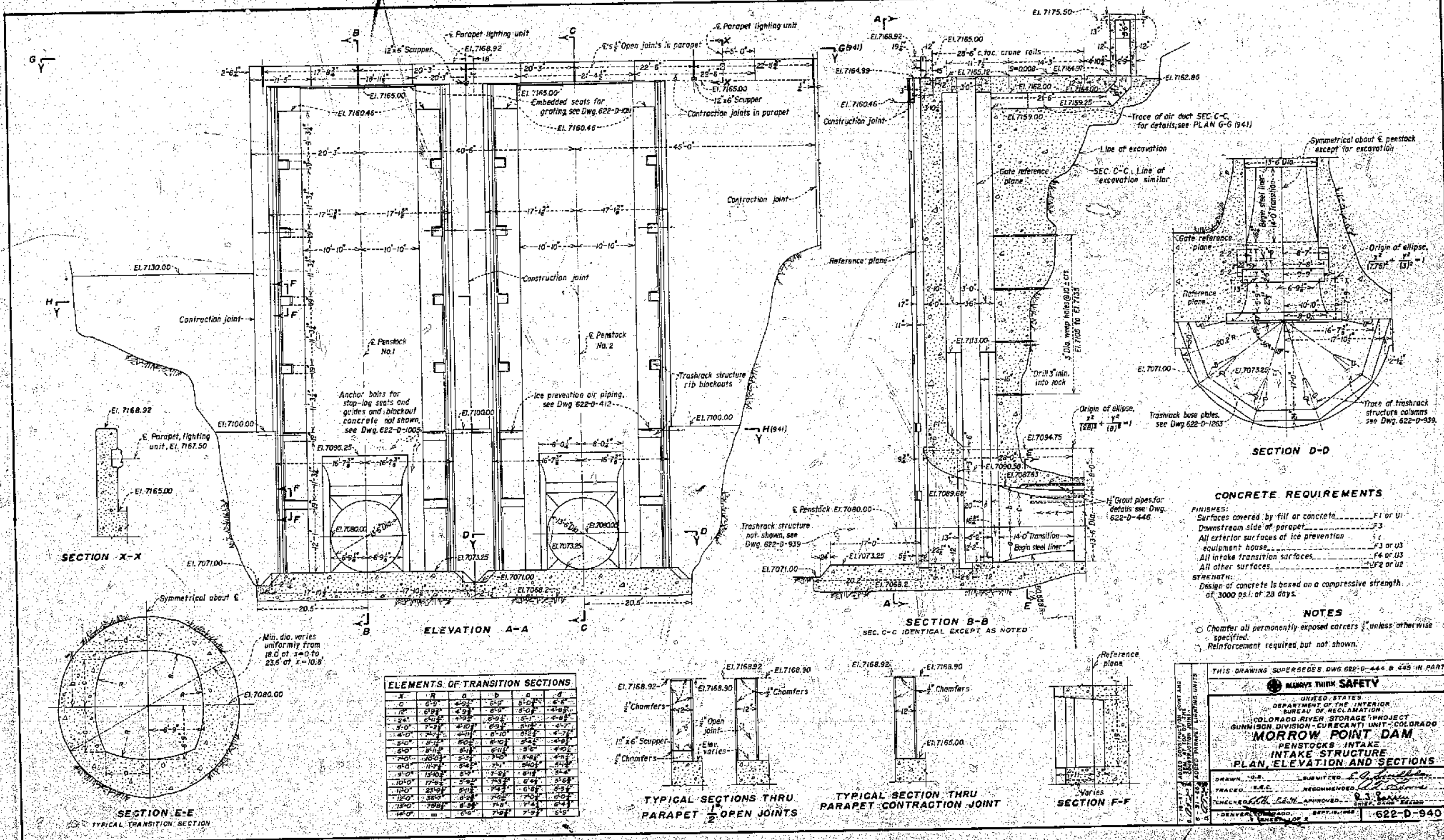
GUNNISON DIVISION—CURECANTI UNIT—COLORADO

MORROW POINT DAM AND POWER PLANT
SECTIONS

DRAWN W.A.T. SUBMITTED
TRACED C.W.B. RECOMMENDED
CHECKED APPROVED
ASST. COMM. AND CHIEF ENGINEER
DENVER, COLORADO, JAN. 18, 1963. 622-D-434



ELEMENTS OF TRANSITION SECTIONS

X	R	a	b	c	d
0	6'-9"	4'-9½"	6'-9"	5'-0½"	4'-6"
12"	6'-9⅛"	4'-9¼"	6'-9"	5'-0⅛"	4'-6½"
24"	6'-11¼"	4'-9¾"	6'-9¼"	5'-1"	4'-8⅜"
3'-0"	7'-2¾"	4'-10¾"	6'-9½"	5'-1¾"	4'-7"
4'-0"	7'-7¾"	4'-11"	6'-10"	5'-2¾"	4'-7¾"
5'-0"	8'-1¾"	5'-0¼"	6'-10½"	5'-4¼"	4'-8¾"
6'-0"	8'-11½"	5'-1¾"	6'-11½"	5'-6"	4'-10½"
7'-0"	10'-0¾"	5'-3¼"	7'-0"	5'-8⅛"	4'-11¾"
8'-0"	11'-7¾"	5'-4⅞"	7'-1"	5'-10½"	5'-1¾"
9'-0"	13'-10½"	5'-7"	7'-2½"	6'-1⅛"	5'-4"
10'-0"	17'-9½"	5'-9½"	7'-3⅝"	6'-4⅛"	5'-6⅜"
11'-0"	23'-9⅛"	5'-11½"	7'-4¾"	6'-8⅛"	5'-9⅞"
12'-0"	38'-7"	6'-2⅜"	7'-6⅝"	7'-0⅜"	6'-0⅛"
13'-0"	78'-8⅛"	6'-5⅝"	7'-8"	7'-4¼"	6'-4⅛"
14'-0"	∞	6'-9"	7'-9¼"	7'-9¼"	6'-9"

CONCRETE REQUIREMENTS

FINISHES:
- Surfaces covered by fill or concrete — F1 or U1
- Downstream side of parapet — F3
- All exterior surfaces of ice prevention equipment house — F3 or U3
- All intake transition surfaces — F4 or U3
- All other surfaces — F2 or U2

STRENGTH:
Design of concrete is based on a compressive strength of 3000 p.s.i. at 28 days.

NOTES

Chamfer all permanently exposed corners ½" unless otherwise specified.
Reinforcement required but not shown.

THIS DRAWING SUPERSEDES DWG. 622-D-444 & 445 IN PART

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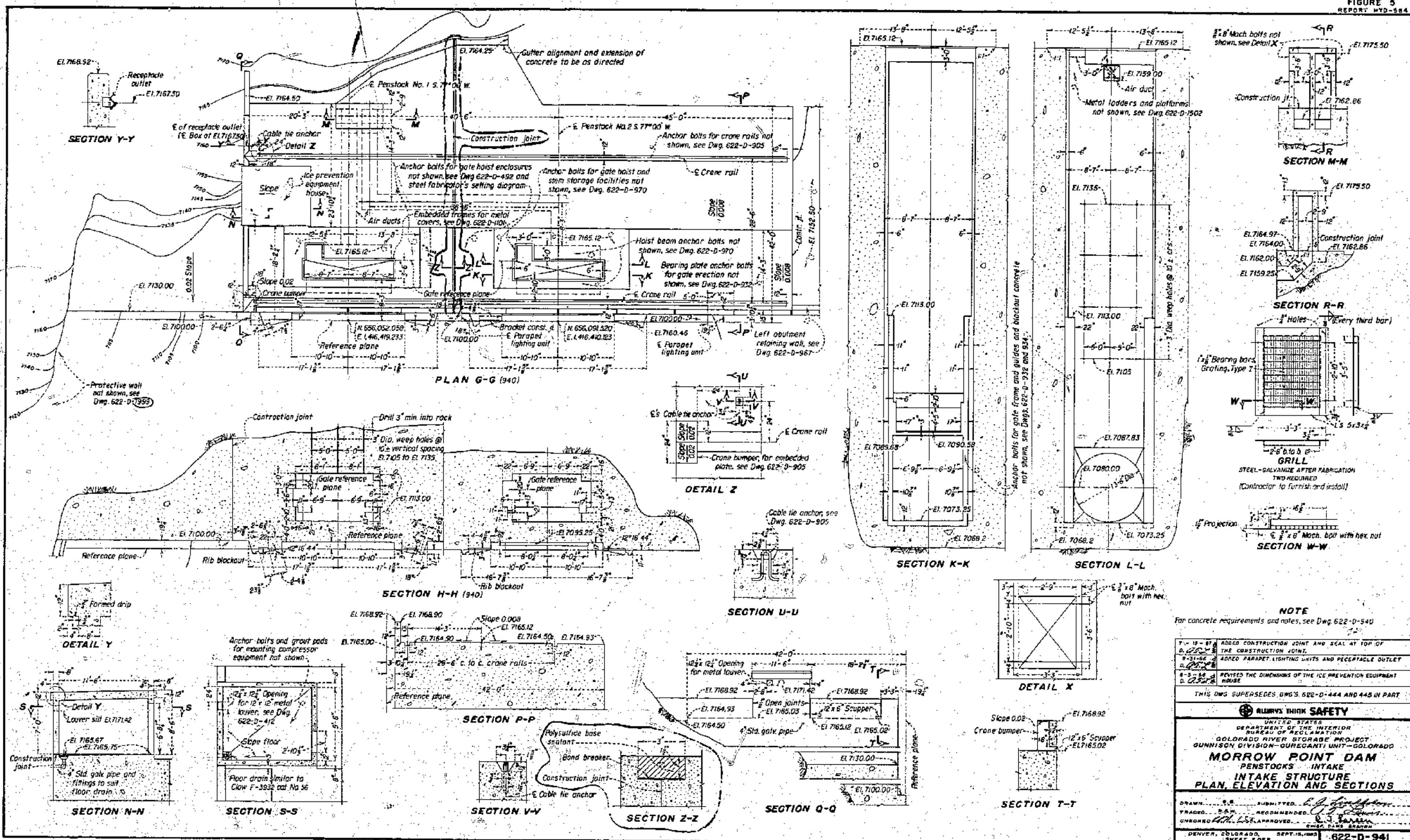
COLORADO RIVER STORAGE PROJECT
GUNNISON DIVISION - CURECANTI UNIT - COLORADO
MORROW POINT DAM
PENSTOCKS INTAKE
INTAKE STRUCTURE
PLAN, ELEVATION AND SECTIONS

DRAWN: G.S. SUBMITTED:
TRACED: E.E.C. RECOMMENDED:
CHECKED: E.E.W. APPROVED: CHIEF, DAMS BRANCH
DENVER, COLORADO, SEPT. 15, 1962
SHEET 1 OF 2
622-D-940

ADDED CONSTRUCTION JOINT AND SEAL AT TOP OF THE CONSTRUCTION JOINT
ADDED PARAPET LIGHTING UNITS


PLAN G-G (940)
SECTION Y-Y
SECTION H-H (940)
DETAIL Z
SECTION U-U
SECTION K-K
SECTION L-L
SECTION M-M
SECTION R-R
GRILL
STEEL-GALVANIZE AFTER FABRICATION
TWO REQUIRED
(Contractor to furnish and install)
SECTION W-W
DETAIL Y
SECTION N-N
SECTION S-S
SECTION P-P
SECTION V-V
SECTION Z-Z
SECTION Q-Q
DETAIL X
SECTION T-T
NOTE
For concrete requirements and notes, see Dwg. 622-D-940
THIS DWG SUPERSEDES DWG'S. 622-D-444 AND 445 IN PART
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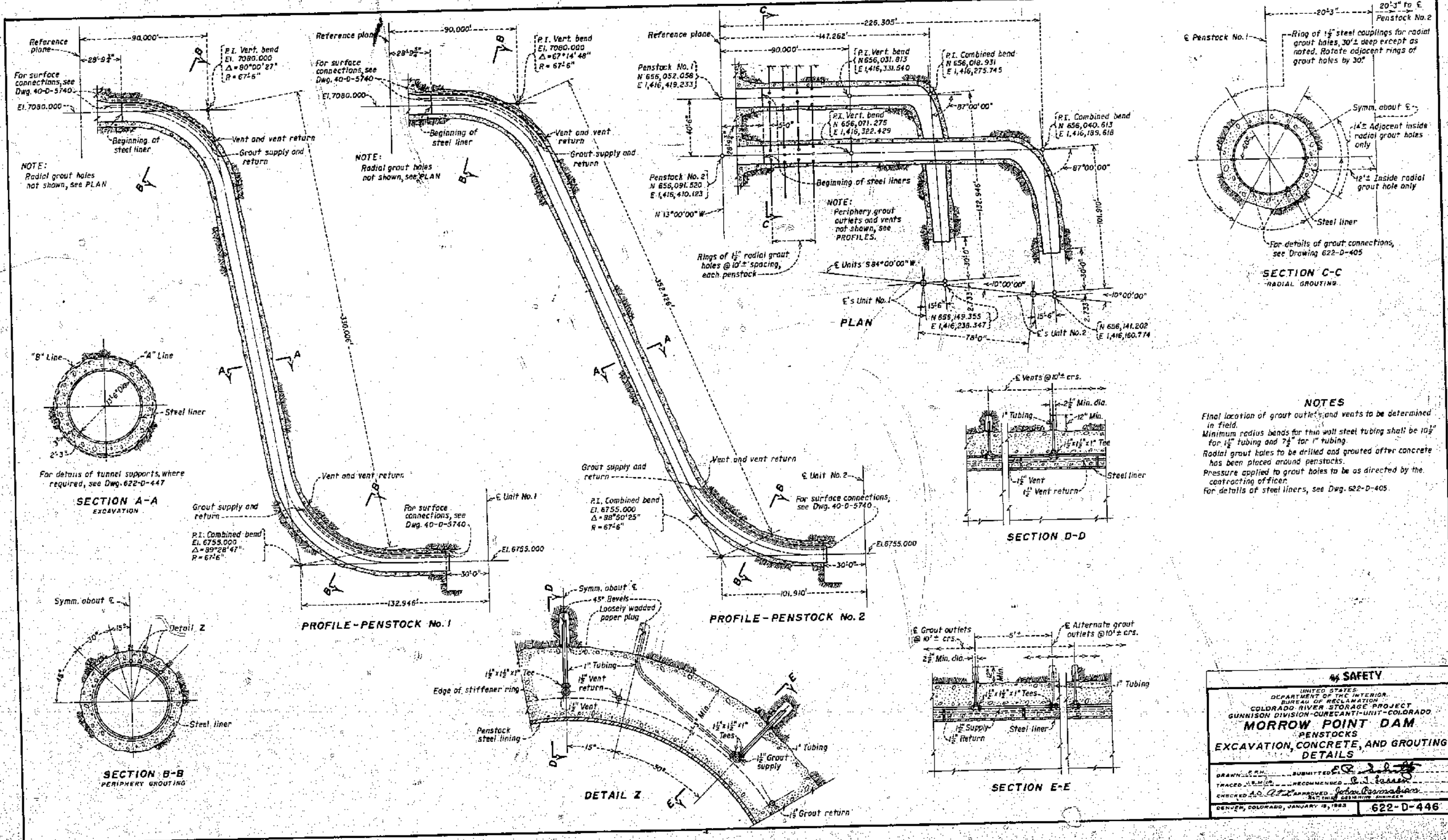
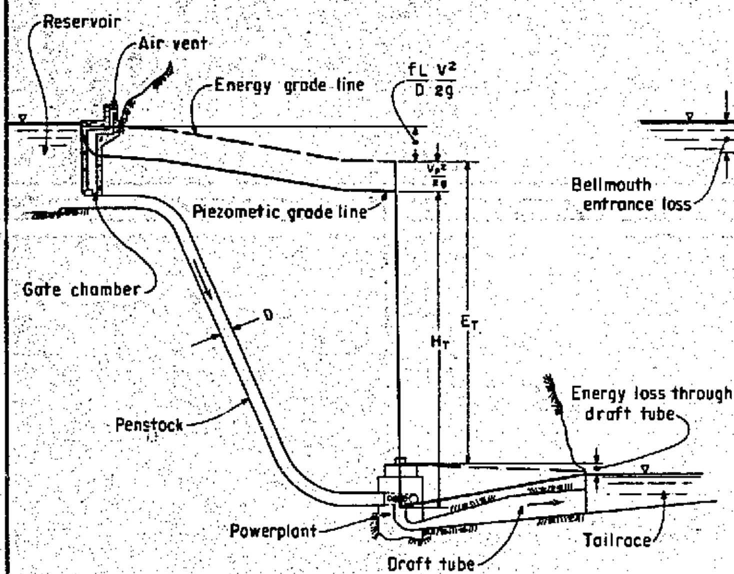
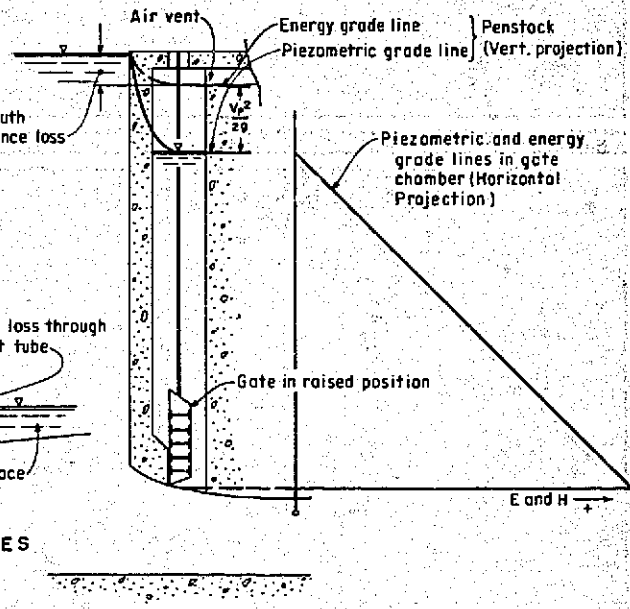
MORROW POINT DAM
PENSTOCKS INTAKE
INTAKE STRUCTURE
PLAN, ELEVATION AND SECTIONS
DENVER, COLORADO
622-D-941

FIGURE 6
REPORT HYD-584

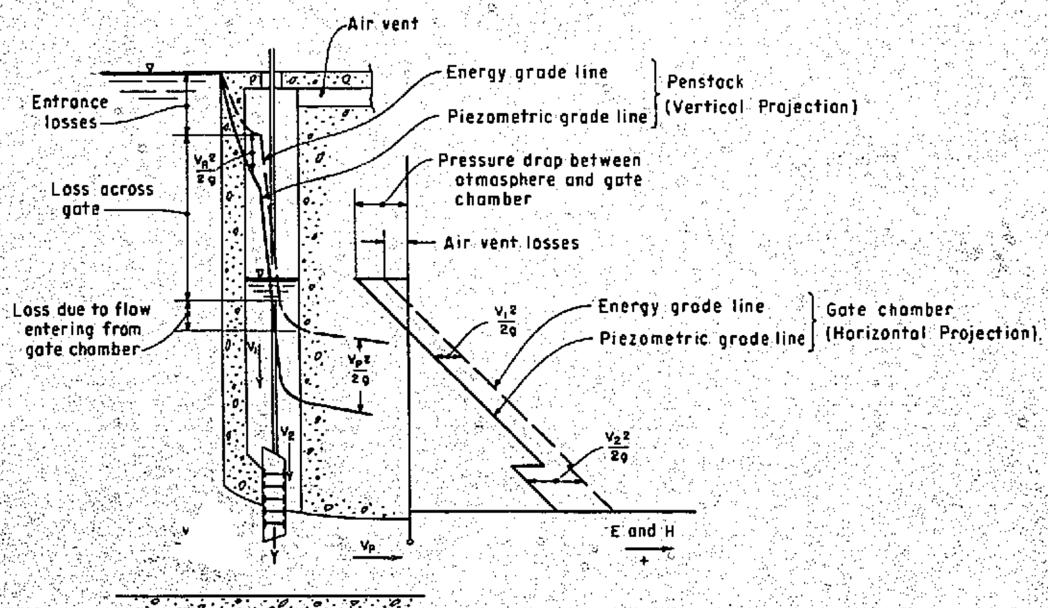




a. ENERGY AND PIEZOMETRIC GRADE LINES IN PENSTOCK AND DRAFT TUBE

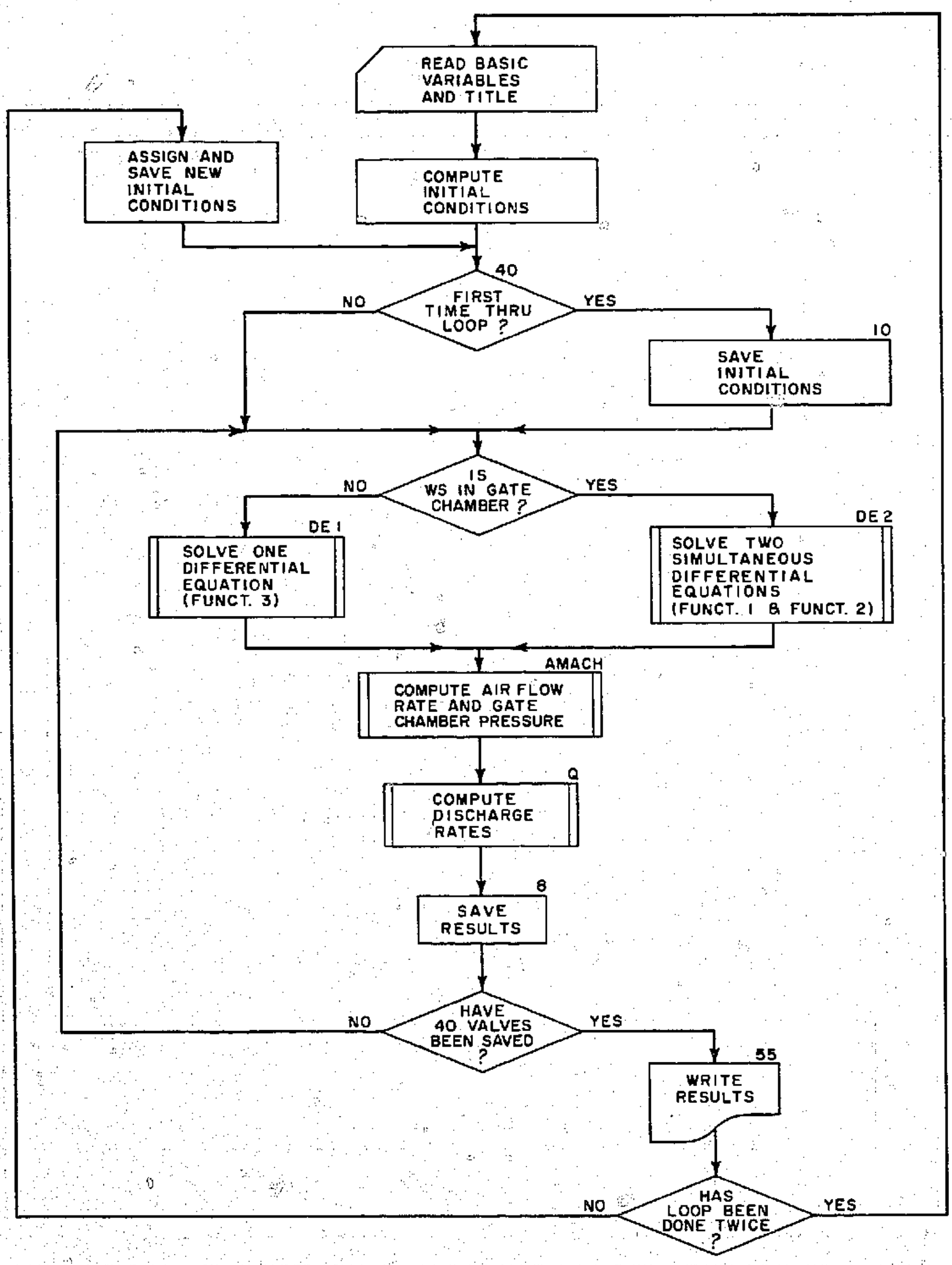


b. ENERGY AND PIEZOMETRIC GRADE LINES AT INTAKE STRUCTURE
(STEADY STATE CONDITION)



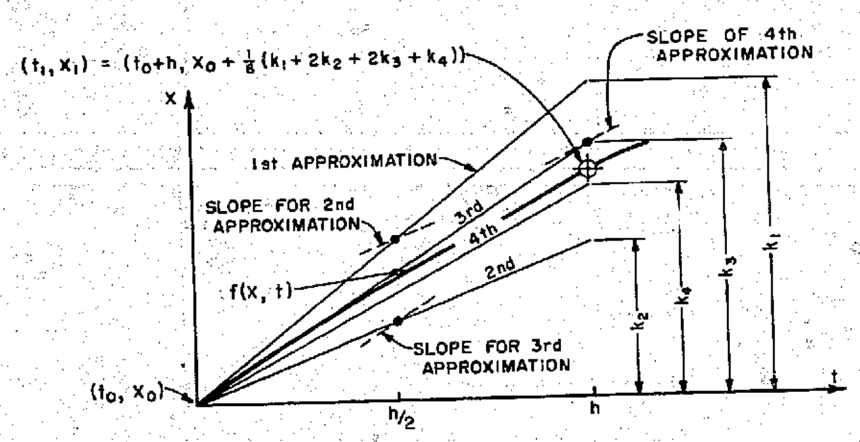
c. ENERGY AND PIEZOMETRIC GRADE LINES AT INTAKE STRUCTURE
(GATE CLOSING)

MORROW POINT DAM
AIR VENT
ENERGY AND PIEZOMETRIC GRADE LINES
BEFORE AND DURING EMERGENCY GATE CLOSURE



MORROW POINT DAM
AIR VENT

FLOW CHART FOR AIR VENT COMPUTATIONS



$k_1 = h f'(t_0, x_0)$

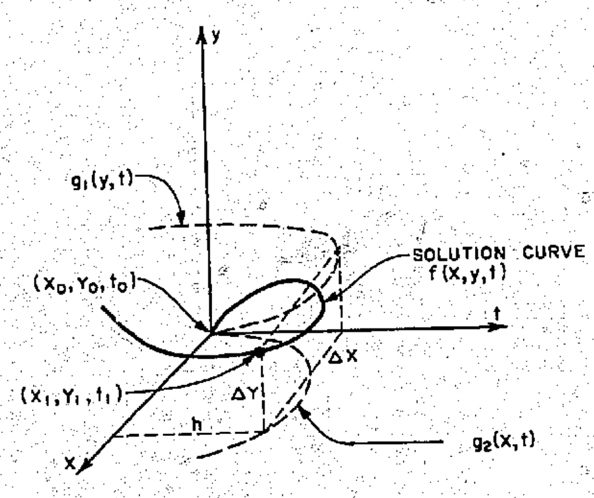
$k_2 = h f'(t_0 + h/2,\ x_0 + k_1/2)$

$k_3 = h f'(t_0 + h/2, x_0 + k_2/2)$

$k_4 = h f'(t_0 + h, x_0 + k_3)$

$f'(t, x)$ = Slope of the function $f(x, t)$ at the coordinates x and t.

A. GRAPHICAL REPRESENTATION OF A DIFFERENTIAL EQUATION BY THE RUNGE-KUTTA METHOD

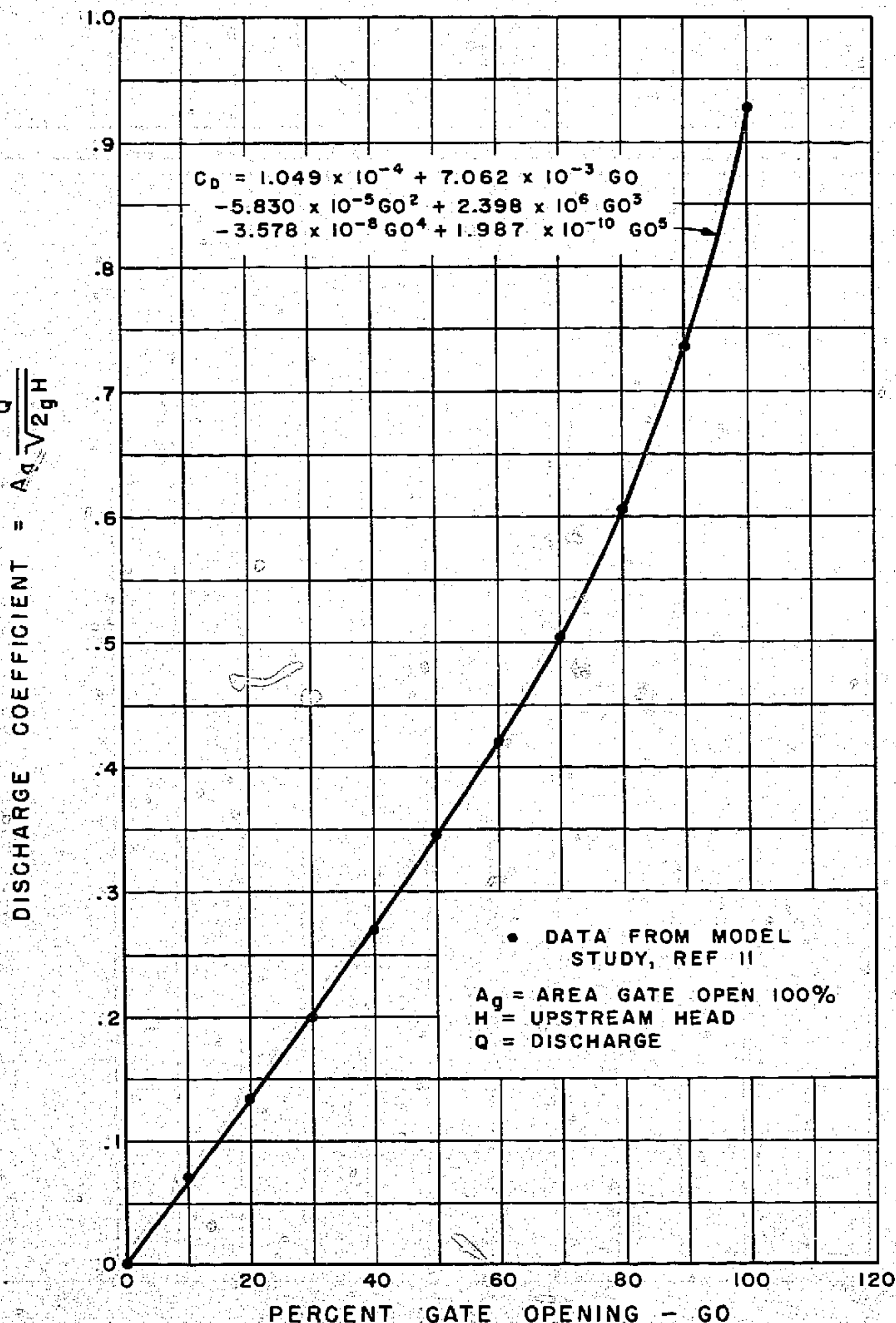


B. GRAPHICAL REPRESENTATION OF THE SIMULTANEOUS SOLUTION OF 2-SECOND ORDER DIFFERENTIAL EQUATIONS

MORROW POINT DAM
AIR VENT

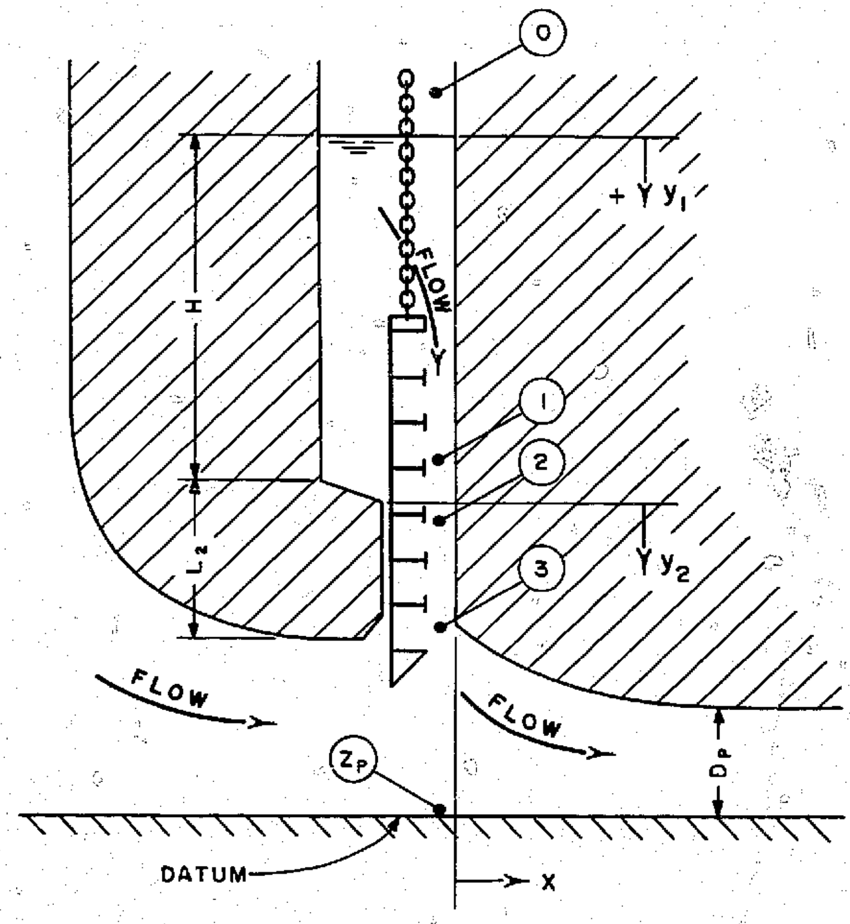
GRAPHICAL REPRESENTATION OF THE SOLUTION OF DIFFERENTIAL EQUATIONS

FIGURE 10
REPORT HYD-584



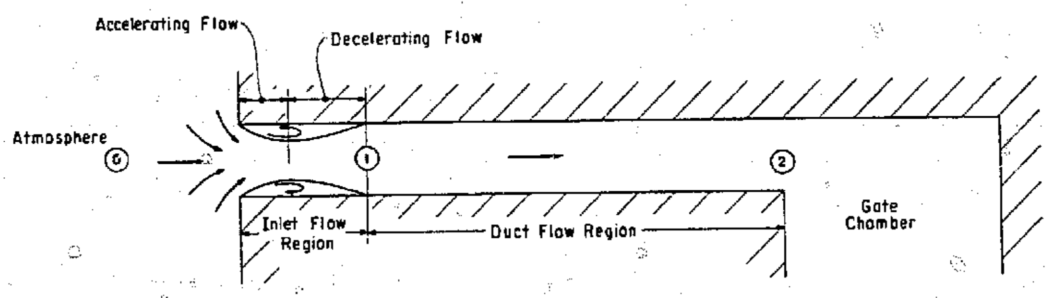
MORROW POINT DAM
AIR VENT
ASSUMED EMERGENCY GATE DISCHARGE COEFFICIENTS

734

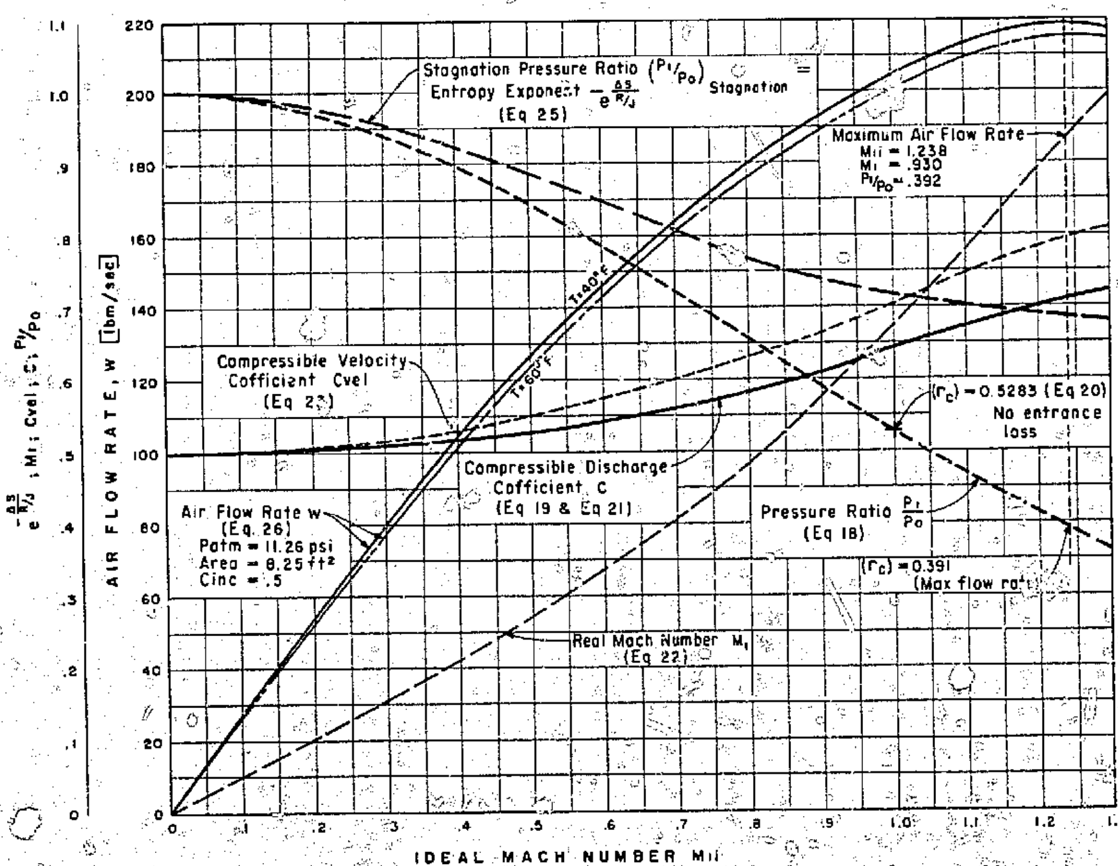


MORROW POINT DAM
AIR VENT

DEFINITION SKETCH FOR FLOW IN VICINITY OF INTAKE TO PENSTOCK

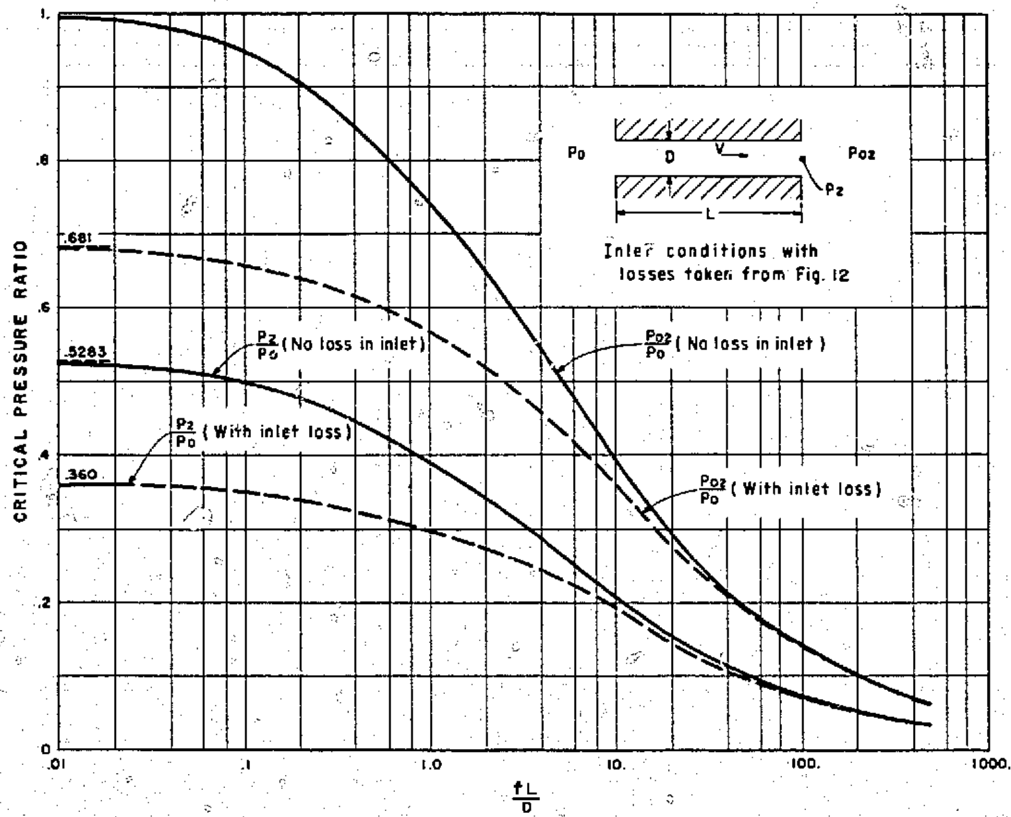


a. DEFINITION SKETCH FOR AIR VENT FLOW



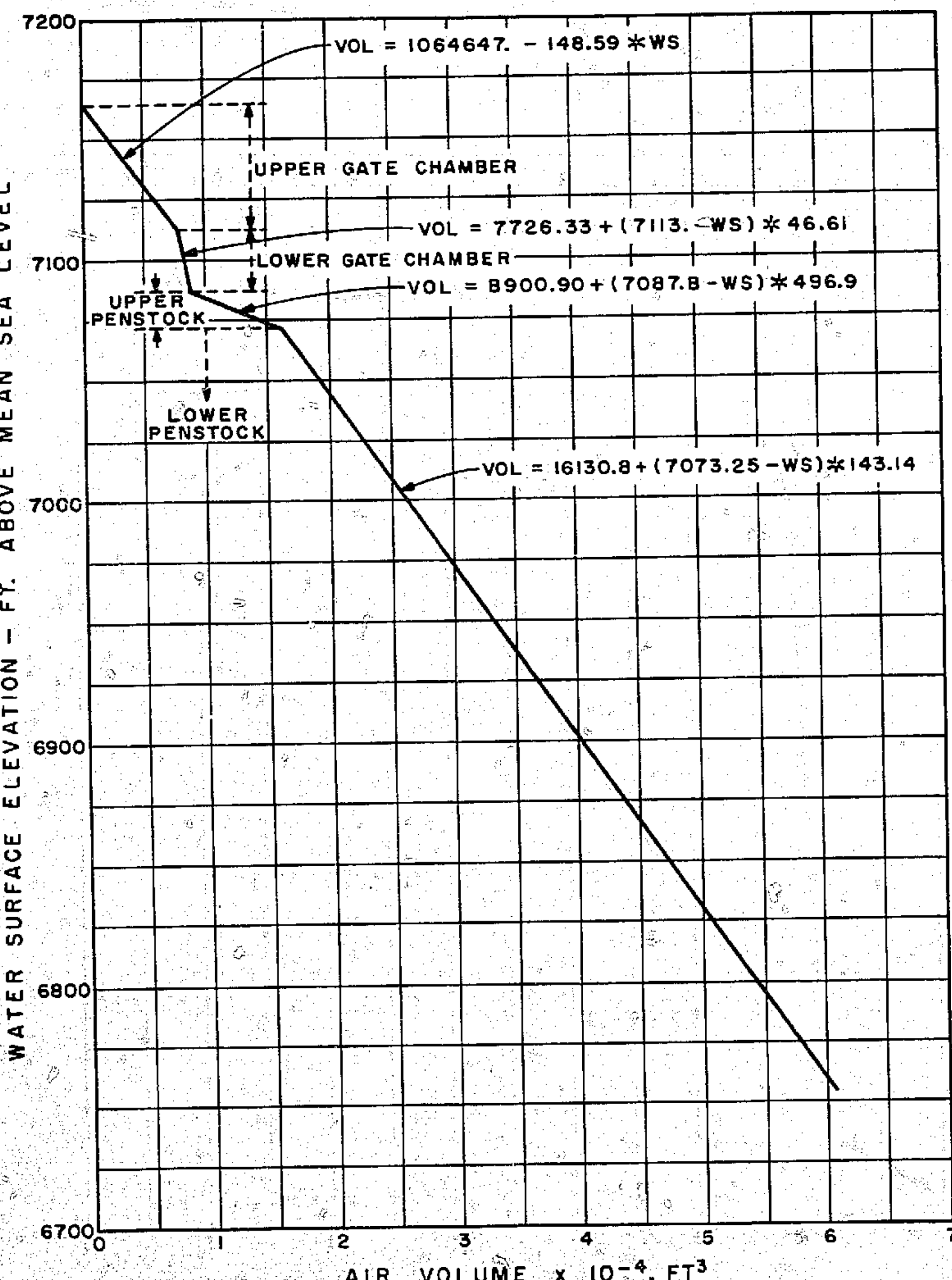
b. FLOW RELATIONSHIPS IN THE INLET FLOW REGION

MORROW POINT DAM
AIR VENT
AIR VENT FLOW



MORROW POINT DAM
AIR VENT
CRITICAL PRESSURE RATIO

FIGURE 14
REPORT HYD-584

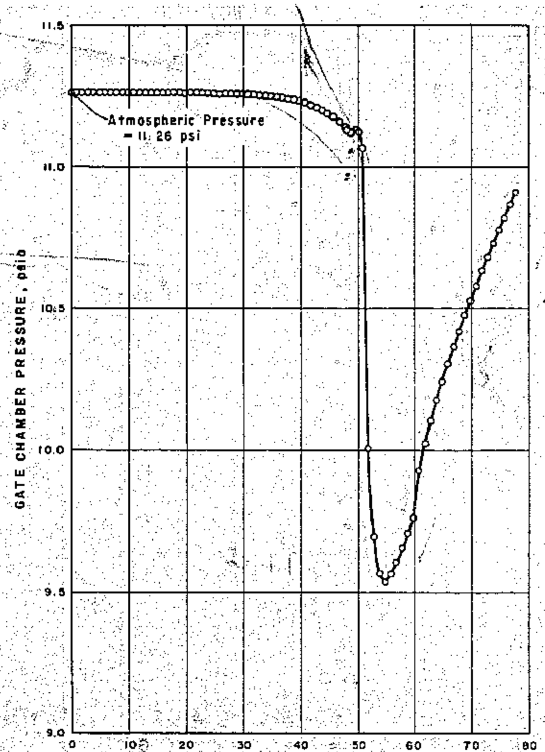


MORROW POINT DAM
AIR VENT

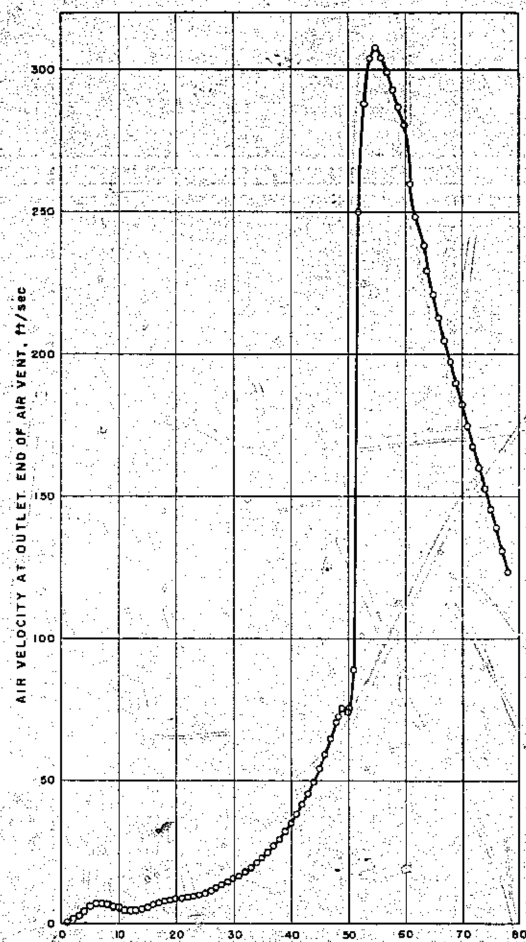
AIR VOLUME IN GATE CHAMBER AND PENSTOCK

734

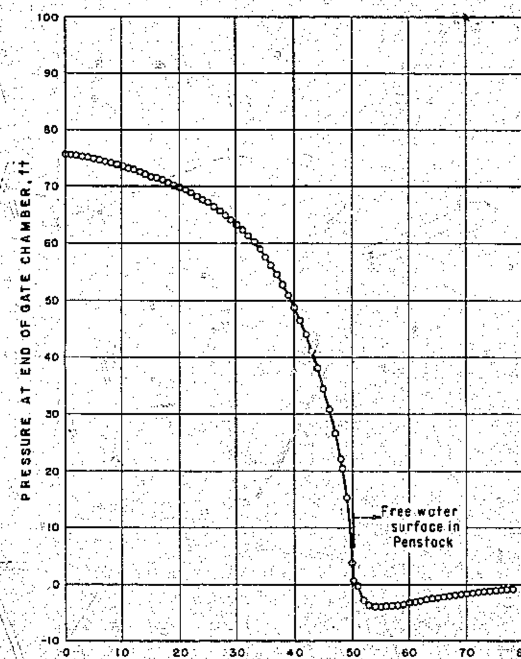
Note: The circles denote computer generated values.



a. ABSOLUTE PRESSURE IN GATE CHAMBER



b. MAXIMUM AIR VELOCITY IN AIR VENT



c. PRESSURE AT LOWEST POINT IN GATE CHAMBER

MORROW POINT DAM
AIR VENT
CRITICAL FLOW PARAMETERS

APPENDIX

7-1782 (9-67)
Bureau of Reclamation

UNITED STATES
DEPARTMENT OF THE INTERIOR
Bureau of Reclamation

ELECTRONIC COMPUTER PROGRAM ABSTRACT

HEADER CARD

DESCRIPTIVE NAME OF PROGRAM 1 AIRFLOW COMPUTATION MORROW POINT DAM 47

AUTHOR 48 FALVEY 72 HT 73 0 80 0

CARD 1

PROGRAM STATUS 1 P DATE 2 010165 7 APPLICATION CODE 8 701 10 COMPUTER 11 H800 26

LANGUAGE 27 FORTRAN 38 STORAGE REQUIRED 39 15000 45 TYPE 46 M

ORIGINATING ORGANIZATION 47 RECLAMATION-OCE 62 DOCUMENTATION 63 YES 66 MAILING CODE 67 D293B 72 73 1 80 1

PURPOSE — CARDS 2 THRU 5

1 COMPUTES FLOW QUANTITIES IN AIR VENT AND PENSTOCK DURING AN EMGERENCY 72 73 2 80 2
GATE CLOSURE. INCLUDES COMPRESSIBLE FLOW EQUATIONS IN VENT. 2 3
2 4
2 5

METHODS — CARDS 6 THRU 8

1 SIMULTANEOUS SOLUTION OF TWO DIFFERENTIAL EQUATIONS USING RUNGE-KUTTA 72 73 3 80 6
METHOD OF NUMERICAL INTEGRATION 3 7
3 8

LIMITATIONS — CARD 9

1 SPECIFIC APPLICATION IS MORROW POINT DAM 72 73 4 80 9

DUPLICATE THE FOLLOWING COLUMNS IN ALL CARDS. FILE NO. 74 H-174 79
SEE REVERSE SIDE FOR INSTRUCTIONS FOR FILLING OUT THE ABSTRACT.

LIST OF SYMBOLS FOR PROGRAM TO COMPUTE AIRFLOW INTO GATE CHAMBER

A. Main Program

ABSPGC - Absolute pressure in the gate chamber (psia)
AD - Cross-sectional area of lower section in gate chamber (ft^2)
ADUCT - Array name for title
AG - Area of emergency gate (ft^2)
AGC - Array name to store ABSPGC
AP - Array name to store QP
AR - Array name to store QR
AREAP - Cross-sectional area of penstock (ft^2)
AS - Array name to store WS
AU - Cross-sectional area of upper section in gate chamber (ft^2)
AVENT - Cross-sectional area of the air vent (ft^2)
AVOL - Volume of air in gate chamber and penstock above the free water surface (ft^3)
AVOLRE - AVOL for steady state condition
C - Compressible discharge coefficient for air
CA - Array name for CD
CD - Emergency gate discharge coefficient
CINC - Incompressible discharge coefficient for air
CKA - Accuracy to which the gate chamber pressure has been computed (psi)
CKB - Array name for CKA
CONST - Constant for an isentropic process
DELT - Time increment for which computations are printed (sec)
DELTIM - Time interval from nearest second to time when water leaves upper section of gate chamber or time when water leaves lower section of gate chamber (sec)
EK - Loss factor between large and small sections of the gate chamber
ENRTAP - Inertia in penstock (ft/sec^2)
ERTAGC - Inertia in gate chamber (ft/sec^2)
FP - Friction factor in penstock
FRICT - Friction coefficient in air vent (Eq 27)
GCR - Time rate of emergency gate closure (%/sec)
HCOL - WSREF minus elevation of entrance to lower gate chamber (ft)
I - Counter
J - Counter
JFIRST - Integer to check for special conditions
JN - Counter
MACHA - Array name for MIR, see subroutine AMACH
MACHGA - Array name for MACHGC
MACHGC - Mach number at gate chamber end of air vent
MACHIN - Mach number at inlet end of air vent

MINC - Percent accuracy to which Mach number must be computed divided by 100
N - Counter
NLPS - Counter
NTIM - Counter
P3 - Pressure at lower end of small section of gate chamber (ft)
PA - Array name for PP
PATM - Atmospheric pressure (psi)
PGA - Array name for PGO
PGC - Gate chamber pressure (ft)
PGCINC - Accuracy to which gate chamber pressure must be computed (psi)
PGO - Percent emergency gate opening (%)
PIN - Pressure in inlet of air vent (psi)
PL - Length of water column in penstock (ft)
PP - Penstock pressure (ft)
QGA - Array name for QGC
QGC - Discharge from gate chamber (cfs)
QP - Discharge from penstock (cfs)
QR - Discharge through emergency gate (cfs)
SPVOL - Specific volume of air (ft^3/lb_m)
SPWTA - Specific weight of air (lb_m/ft^3)
SPWTAG - Array name for SPWTA
T - Elapsed time from beginning of gate closure for which output is printed (sec)
TLOSS - Loss factor across turbine
TOUT - Time at which water leaves large section of gate chamber or time at which water leaves small section of gate chamber (sec)
VEL2 - Velocity at which water leaves large section of gate chamber or velocity at which water leaves small section of gate chamber (ft/sec)
VGC - Velocity of the free water surface in the gate chamber (ft/sec)
VIN - Air velocity in inlet section of air vent (ft/sec)
VOLGC - Volume of water in gate chamber between last time increment and time water leaves the gate chamber (ft^3)
VOUT - Air velocity in outlet section of air vent (ft/sec)
VP - Water velocity in penstock (ft/sec)
WS - Free water surface elevation in gate chamber or penstock
WSREF - Free water surface elevation in gate chamber for steady state condition
WSTEST - Dummy variable to check location of free water surface in gate chamber
WTAIR - Weight of air in gate chamber and penstock (lb)
WTFLA - Airflow rate through air vent (lb_m/sec)
X - Distance particle of water moves in penstock after gate begins closing (ft)
Y - Distance water surface falls in gate chamber after gate begins closing (ft)

B. Subroutine Q

GATEZ - Elevation of bottom of emergency gate

All other symbols are defined in main program.

C. Subroutine DE2

AI-3
AKI-4
ALI-4 Dummy variables used in the integration
AMI-4
API-4
BI-3
CI-3
DI-3
DELF
DEL2F
DEL3F
DEL4F
DEL G
DEL2G
DEL3G
DEL4GEI-3
F
FC
FL
G
GC
GL
RKT
RKVX
RKVY
RKX
RKY
H - Small increment of time which is one fifth as large as DELT
DEL X - Incremental change in X determined from the integration for time interval H
DELTVX - Incremental change in VX determined from the integration for time interval H
DELTY - Incremental change in Y determined from the integration for time interval H
DELTVY - Incremental change in VY determined from the integration for time interval H
I
J Counters
K
VX - VP in main program
VY - VGC in main program

All other variables are defined in the main program.

D. Subroutine DELTD

DEL -
DEL2 - Dummy variables used in computing the fourth difference
DEL3 - of a series of five quantities
DEL4 - The fourth difference
A - An array of five quantities

All other variables are defined in the main program.

E. Function FUNCTI

FUNCTI - The inertia of flow in the gate chamber (ft/sec^2)
PT - The pressure at the lower end of the small section of the gate chamber (ft)
PVAPOR - Vapor pressure of water (ft)
VHGC - Velocity head in the gate chamber (ft)
VHP - Velocity head in the penstock (ft)
VHR - Velocity head immediately downstream from the emergency gate

AA-X
BA-Y
CA-VX From Subroutine DE2
DA-VY
EA-T

All other variables are defined in the main program.

F. Function FUNCT2

FUNCT2 - The inertia of flow in the penstock (ft/sec^2)

AB-X
BB-Y
CB-VX From Subroutine DE2
DB-VY
EB-T

All other variables are defined in the main program.

G. Subroutine DE1

AI
A3
AKI-4
BI-3
CI

C3
DELF
DEL2F
DEL3F
DEL4F — Dummy variables used in the integration
DELTX
F
FC
RF
RT
RVX
RX

H - Same definition as in Subroutine DE2
VX - VP in main program
K - counter

All other variables are defined in the main program.

H. Function FUNCT3

FUNCT3 - The inertia of flow in the penstock (ft/sec^2)
AC - X in the main program
BC-VP in the main program
DC - T in the main program
DQRDT - Time rate of change of Qk (cfs/sec^2)
DWS - Difference between free water surface in penstock and tailwater elevation (ft)
GATEZ - Elevation of bottom of emergency gate
VHP - Velocity head in the penstock (ft)

All other variables are defined in the main program.

I. Subroutine AMACH

AVOLU - Air volume above elevation 7113
CK - Sum of all the terms in EQ 31
CKASAV - Dummy variable to save CKA
CKM - Dummy variable to save CK
DCKDM - Derivative of CK with respect to MACHGC
DEQDM - Derivative of EQ with respect to MACH
DM1I - Incremental change in M1I

Ratio between stagnation pressure at end of inlet section in air vent and atmospheric pressure
EQ - Evaluation of EQ 29 for a given Mach number
DQLH - EQ with Mach number = MACHIN
EQRH - EQ with Mach number = MACHGC

JCK
JN
K
KK

Counters

M1I - Ideal Mach number in inlet section of air vent
M1R - Real Mach number in inlet section of air vent
MACH - Dummy variable replacing given Mach number in the expression EQ
MACSAV - Dummy variable to save MACHIN
MM -
MOON -
N -
NDO -
NWP -

Counters

PGCTRL - Gate chamber pressure based on Mach numbers (psi)
PGCTST - Gate chamber pressure based on adiabatic expansion of air in gate chamber (psi)
PGCSAV - Dummy variable to save ABSPGC
PIN - Stagnation pressure at end of inlet region in air vent (psi)
R - Ratio between atmospheric pressure and pressure in inlet section of air vent
RADICL - Dummy variable used in computing MIR
RC - Critical pressure ratio in inlet section of air vent
RNLUP - Dummy variable
ROOT - Dummy variable used in computing MIR

All other variables are defined in the main program.

COMPUTER REQUIRED

The program conforms to USASI specifications for FORTRAN IV and is compatible with most computers using FORTRAN IV compilers. The program as written has been run on a Honeywell H-800 and a Control Data CDC 6400 computer.

RUNNING TIME

With the CDC 6400, 18 seconds of central processer time and 7 seconds input/output time are required. About 15,000 words of core memory are needed for the program.

With the Honeywell H-800, about 7 minutes of central processer time are required for compilation and execution. Of this time, 3 minutes are required for compilation. Core memory required is 7,378 words.

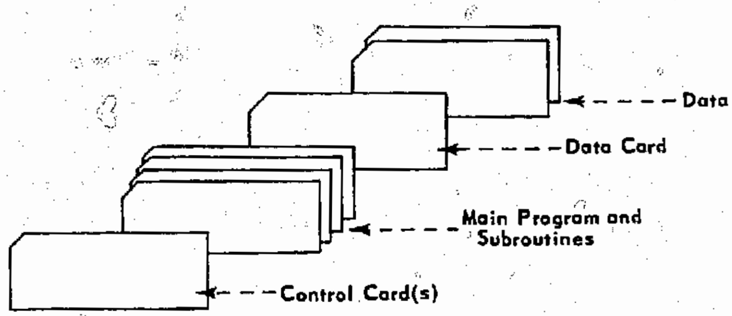
PREPARATION OF INPUT DATA

The input data consist of variables which the user will want to vary to determine their effect on the solution. These include:

- the time increment for which output is required
- atmospheric pressure
- specific weight of air
- cross-sectional area of air vent
- air vent friction factor
- emergency gate closing rate
- accuracy to which gate chamber pressure must be determined
- accuracy to which outlet Mach number must be determined for a given inlet Mach number
- title for the type of air vent studied

The first eight values of input data should be placed in Columns 1-64 of the first data card using an F8.4 format. The title should be placed in Columns 1-72 of the second data card using an 12A6 format. The title should be centered about Column 37 of the title card.

The deck should be stacked according to the following diagram:



PROGRAM LISTING

```
C     COMPUTATION OF AIR FLOW INTO GATE CHAMBER DURING AN EMERGENCY
C        CLOSURF OF GATES FOR THE PENSTOCK INTAKE STRUCTURE
C                         MORROW POINT DAM
      REAL MINC
      REAL MACHA,MACHGA
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),J
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      DIMENSION ADUCT(12),QGA(50),AR(50),AP(50),AS(50),AGC(50),
     1VIN(50),VOUT(50),PA(50),PGA(50),CA(50),ERTAGC(50),
     2 SPWTAG(50),SPVOL(50),
     3CKB(50),X(50),Y(50),VP(50),VGC(50)
    1 READ(2,2)DELT,PATM,SPWTA,AVENT,FRICT,GCR,PGCINC,MINC
    2 FORMAT(8F8.4)
    3 READ(2,4)(ADUCT(I),I=1,12)
    4 FORMAT(12A6)
      WRITE(3,111)
  111 FORMAT(1H1,//)
C
C     INITIAL CONDITIONS
C
      CD= .9303049                                                      *
      PL= 471.                                                          *
      FP= .009                                                          *
      TLOSS= 82.75                                                      *
      AU= 148.59                                                        *
      AD= 46.61                                                         *
      AREAP= 143.14                                                     *
      AG= 222.13                                                        *
      QR= AREAP*SQRT(405.*64.4/(TLOSS-1.+FP*PL/13.5+(AREAP/AG/CD)**2))  *
      PP= 91.75-(QR/AG/CD)**2/64.4                                      *
      QP = QR
      QGC = 0.
      WS = PP + 7073.25                                                 *
      WSREF = WS
      HCOL= WSREF-7113.                                                 *
      AVOLRE = 1064647. - 148.59*WS                                     *
      WTAIR = SPWTA * AVOLRE
      AVOL= AVOLRE
      CINC = .5                                                         *
      ABSPGC = PATM
      PIN = PATM
      MACHIN = 0.
      MACHGC = 0.
      PGC = 2.30769*PATM
      CONST = PATM / SPWTA**1.4
      CKA= 0.
      T(1)= 0.
      EK= .8                                                            *
      JFIRST= 1
      DELTIM= 0.
      NTIM= 0
```

```
C
C     COMPUTATIONS IN MAIN LOOP
   40 NTIM= NTIM+1
      J= NTIM-1
      NLPS= NTIM*40-J
      IF(NTIM.LE.1)GO TO 45
C
C     SECOND TIME THRU
      JFIRST= 2
      T(1)= T(41)
      QGA(1)= QGA(41)
      AR(1)= AR(41)
      AP(1)= AP(41)
      VP(1)= VP(41)
      VGC(1)= VGC(41)
      X(1)= X(41)
      Y(1)= Y(41)
      AS(1)= AS(41)
      AGC(1)= AGC(41)
      VIN(1)= VIN(41)
      VOUT(1)= VOUT(41)
      PGA(1)= PGA(41)
      CA(1)= CA(41)
      ENRTAP(1)= ENRTAP(41)
      ERTAGC(1)= ERTAGC(41)
      PA(1)= PA(41)
      MACHA(1)= MACHA(41)
      MACHGA(1)= MACHGA(41)
      SPWTAG(1)= SPWTAG(41)
      SPVOL(1)= SPVOL(41)
      WTFLA(1)= WTFLA(41)
      CKB(1)= CKB(41)
      P3(1)= P3(41)
C
   45 J= J+1
      JN= J-1
      IF(JFIRST.EQ.1)GO TO 10
      IF(JFIRST.GE.6) GO TO 35
      IF(J.LE.6)GO TO 30
      WSTEST= AS(J-4)-4.*DELT*(2.*VGC(J-1)-VGC(J-2)+2.*
     1VGC(J-3))/3.
      IF(WSTEST.LE.7087.8)GO TO 35
      IF(WSTEST.LE.7113.)GO TO 37
      GO TO 30
C
C     WATER SURFACE IN PENSTOCK
C
   35 IF(JFIRST.EQ.6)GO TO 41
      IF(JFIRST.EQ.7)GO TO 42
      IF(JFIRST.EQ.8)GO TO 60
      VOLGC= (AS(JN)-7087.8)
      TOUT= T(JN)+VOLGC/VGC(JN)
      VEL2= VGC(JN)+FUNCT2(X(JN),Y(JN),VP(JN),VGC(JN),T(JN))*
     1(TOUT-T(JN))
      DELTIM= (AS(JN)-7087.8)*2./(VEL2+VGC(JN))
      T(J)= T(J-1)+DELTIM
      CALL DE2(X,Y,VP,VGC,T,DELTIM,JN,JN)
      JFIRST= 6
```

```
      AS(J)= WSREF-Y(J)
      WS= AS(J)
      WSREF= AS(J)
      X(J) = 0.
      CALL AMACH(CINC,MINC,FRICT,AVENT,DELTIM,PGCINC,WTAIR,CONST,
     1CKA)
      GO TO 7
   41 DELT= DELT-DELTIM
      JFIRST= 7
      GO TO 60
   42 DELT= DELT+DELTIM
      JFIRST= 8
   60 CALL DE1(X,VP,T,DELT,JN)
      AS(J)= WS
      GO TO 70
C
C     WATER SURFACE IN LOWER GATE CHAMBER
C
   37 IF(JFIRST.EQ.3)GO TO 38
      IF(JFIRST.EQ.4)GO TO 39
      IF(JFIRST.EQ.5)GO TO 30
      VOLGC= (AS(JN)-7113.)
      TOUT= T(JN)+VOLGC/VGC(JN)
      VEL2= VGC(JN)+FUNCT2(X(JN),Y(JN),VP(JN),VGC(JN),T(JN))*
     1(TOUT-T(JN))
      DELTIM= (AS(JN)-7113.)*2./(VEL2*VGC(JN))
      T(J)= T(J-1)+DELTIM
      CALL DE2(X,Y,VP,VGC,T,DELTIM,JN,JN)
      JFIRST= 3
      AS(J)= WSREF-Y(J)
      WS= AS(J)
      CALL AMACH(CINC,MINC,FRICT,AVENT,DELTIM,PGCINC,WTAIR,CONST,
     1CKA)
      GO TO 7
   38 DELT= DELT-DELTIM
      JFIRST= 4
      GO TO 30
   39 DELT= DELT+DELTIM
      JFIRST= 5
      GO TO 30
C
   30 CALL DE2(X,Y,VP,VGC,T,DELT,JN,JN)
      AS(J)= WSREF-Y(J)
      WS= AS(J)
   70 CALL AMACH(CINC,MINC,FRICT,AVENT,DELT,PGCINC,WTAIR,CONST,
     1CKA)
      IF(JFIRST.GE.7)P3(J)= 2.30769*(ABSPGC-PATM)
      GO TO 7
C
C     ASSIMILATION OF RESULTS
C
   10 QGA(1)= QGC
      AR(1)= QR
      AP(1)= QP
      VP(1)= AP(1)/143.14
      VGC(1)= 0.
      X(1)= 0.
      Y(1)= 0.
```

```
      AS(1)= WS
      AS(2)= WS
      AGC(1)=ABSPGC
      VIN(1)= 0.
      VOUT(1)= 0.
      ENRTAP(J)= FUNCT1(X(J),Y(J),VP(J),VGC(J),T(J))*PL/32.2*(-1.)        *
      ERTAGC(J)= FUNCT2(X(J),Y(J),VP(J),VGC(J),T(J))*(WSREF-7113.+AU/     *
     1AD*25.2)*(-1.)/32.2
      PGA(1)= PGO
      CA(1)= CD
      PA(1)= PP
      MACHA(1)=  0.
      MACHGA(1)= 0.
      SPWTAG(1)= SPWTA
      SPVOL(1)=  1./SPWTA
      WTFLA(1)=  0.
      CKB(1)=    0.
      JFIRST= 2
    6 GO TO 11
    7 CALL Q(QGC,VP,VGC)
    8 QGA(J)= QGC
      IF(JFIRST.EQ.100)GO TO 55
      AR(J)= QR
      AP(J)= QP
      AGC(J)=ABSPGC
      IF(JFIRST.GE.7) GO TO 85
      ENRTAP(J)= FUNCT1(X(J),Y(J),VP(J),VGC(J),T(J))*PL/32.2*(-1.)        *
      ERTAGC(J)= FUNCT2(X(J),Y(J),VP(J),VGC(J),T(J))*(WS   -7113.+AU/     *
     1AD*25.2)*(-1.)/32.2                                                 *
      IF(WS.LE.7113.)ERTAGC(J)= FUNCT2(X(J),Y(J),VP(J),VGC(J),T(J))       *
     1*AU/AD*(WS-7087.8)*(-1.)/32.2
      GO TO 80                                                            *
   85 ENRTAP(J)= FUNCT3(X(J),VP(J),T(J))*(6616.8-WS)/32.2
      ERTAGC(J)= 0.
   80 WTAIR= WTAIR+(WTFLA(JN)+WTFLA(J))*DELT/2.
      IF(JFIRST.EQ.3.OR.JFIRST.EQ.6)WTAIR= WTAIR+(WTFLA(JN)
     1+WTFLA(J))*(DELTIM-DELT)/2.
      IF(JCK.EQ.3)WTAIR= WTAIR+(WTFLA(J)-WTFLA(JN))*DELT/2.
      SPWTAG(J)= WTAIR/AVOL
      SPVOL(J)= 1./SPWTAG(J)
      PGA(J)= PGO
      PA(J)= PP
      CA(J)= CD
      VOUT(J)= MACHGA(J)*SQRT(32.2*SPVOL(J)*1.4*AGC(J)*144.)
      IF(AGC(J).GE.PATM)GO TO 20                                          *
      VIN(J)= C*2449.4*SQRT(1.-(AGC(J)/PATM)**(2./7.))
      GO TO 21
   20 VIN(J)= VOUT(J)
   21 CKB(J)= CKA
      IF(JFIRST.EQ.10)GO TO 55
   11 IF(J.LT.NLPS)GO TO 45
C
C     WRITE STATEMENTS FOR OUTPUT OF RESULTS
C
   55 J= JN+1
      IF(JFIRST.EQ.100) J=J-1
      WRITE(3,12) PATM,SPWTA,(ADUCT(I),I=1,12)
```

```
 12 FORMAT (1H1,8X,56H COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER D
   1URING AN / 16X,40H EMERGENCY GATE CLOSURE IN THE PENSTOCK- / 27X,
   218H INTAKE STRUCTURE  / 27X,18H MORROW POINT DAM  // 8X,22H ATMOSP
   3HERIC PRESSURE ,12X, 24H SPECIFIC WEIGHT OF AIR  / 15X, F6.2, 5H P
   4SI , 23X,F6.4, 11H LB/CU.FT.   // 12A6 //)
    WRITE(3,13)(T(N),QGA(N),AR(N),AP(N),AS(N),AGC(N),VIN(N),VOUT(N),
   1N=1,J)
    IF(JFIRST.EQ.100)WRITE(3,120)T(J+1)
120 FORMAT(4X,F8.1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER )
 13 FORMAT(5X,64H  TIME       Q        Q       Q        WS      GATE     INL
   1ET  OUTLET  /5X,64H              GATE      RES  PENSTOCK  ELEV  CHAMBER
   2 AIR VEL  AIR VEL /5X,64H          CHAMBER
   3 PRESS                  /5X,64H  (SEC)    (CFS)    (CFS)    (CFS)
   4       (PSIA) (FT/SEC)(FT/SEC) //(4X,4F8.1,F8.2,1X,F8.3,2F8.1))
    WRITE(3,12) PATM,SPWTA,(ADUCT(I),I=1,12)
    WRITE(3,14)(T(N),P3(N),PA(N),PGA(N),CA(N),ERTAGC(N),ENRTAP(N),N=1,
   1J)
    IF(JFIRST.EQ.100)WRITE(3,100)T(J+1)
100 FORMAT(7X,F8.1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER )
 14 FORMAT(8X,56H  TIME     PRESS PENSTOCK  GATE    COEFF   INERTIAL TER
   1MS  /8X,56H             AT 3     PRESS  OPENING DISCH.   GATE  PENSTOC
   2K  /8X,32H  (SEC)     (FT)      (FT)      (O/O)   //(7X,F8.1,2F8.2,F8.1,
   3F8.4,2F8.4))
    WRITE(3,12) PATM,SPWTA,(ADUCT(I),I=1,12)
    WRITE(3,15)(T(N),MACHA(N),MACHGA(N),SPWTAG(N),SPVOL(N),WTFLA(N),
   1CKB(N),N=1,J)
    IF(JFIRST.EQ.100)WRITE(3,100)T(J+1)
 15 FORMAT(8X,56H  TIME  MACH NO.MACH NO.SPECIFICSPECIFICAIR FLOWACCUR
   1ACY /8X,56H            AT        AT     WEIGHT  VOLUME   RATE  OF PRES
   2S /8X,56H          INLET  OUTLET  OF AIR  OF AIR          CALC.  /
   38X,56H  (SEC)                   LB/CU FTCU FT/LBLBM/SEC  (PSI)    //
   4(7X,F8.1,3F8.4,2F8.2,F8.4))
    WRITE(3,16)(QGA(J),AR(J),AP(J),VP(J),VGC(J),X(J),Y(J),AS(J),
   1AGC(J),VIN(J),VOUT(J),PGA(J),CA(J),ENRTAP(J),ERTAGC(J),
   2PA(J),MACHA(J),MACHGA(J),SPWTAG(J),SPVOL(J),WTFLA(J),CKB(J))
 16 FORMAT(1H1,(9X,4E13.6))
    IF(JFIRST.EQ.100)GO TO 110
    IF(NTIM.LE.1)GO TO 40
110 CONTINUE
    GO TO 1
    END
```

```
      SUBROUTINE Q(QGC,VP,VGC)
      REAL MACHA,MACHGA
      DIMENSION VP(50),VGC(50)
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),N
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      QP= VP(N)*AREAP
    2 IF(JFIRST.GT.6)GO TO 3
      QGC=VGC(N)*AU
      IF(JFIRST.GT.3)QGC= VGC(N)*AD
      GO TO 4
    3 QGC=0.
    4 QR= QP-QGC
      IF(JFIRST.GE.7)QR= AG*CD*SQRT(64.4*(91.75-PGC+2.30769*PATM))          *
      GATEZ= 7073.25+13.5*PGO/100.                                          *
      IF(JFIRST.GE.7.AND.WS.GE.GATEZ)QR= AG*CD*SQRT(64.4*(91.75-PP+PGC      *
     1-2.30769*PATM))
      RETURN
      END
```

```
      SUBROUTINE DE2 (X,Y,VX,VY,U,DELT,N,NT)
      REAL MACHA,MACHGA
      DIMENSION X(50),Y(50),VX(50),VY(50),RKT(5),RKX(5),
     1RKY(5),RKVX(5),RKVY(5),F(5),G(5),U(50)
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),IDUD
     2,PL,FP,TLOSS,AU,AD,ABEAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      RKX(1)= X(N)
      RKY(1)= Y(N)
      RKVX(1)= VX(N)
      RKVY(1)= VY(N)
      IF(JFIRST.EQ.4)RKVY(1)= RKVY(1)*AU/AD
      RKT(1)= T(N)
      H= DELT/5.
      F(1)= FUNCT1(RKX(1),RKY(1),RKVX(1),RKVY(1),RKT(1))
      G(1)= FUNCT2(RKX(1),BKY(1),RKVX(1),RKVY(1),RKT(1))
      DO 100 K=1,4
      AK1= RKVX(K)*H
      AL1= RKVY(K)*H
      AM1= H*FUNCT1(RKX(K),RKY(K),RKVX(K),RKVY(K),RKT(K))
      AP1= H*FUNCT2(RKX(K),RKY(K),RKVX(K),RKVY(K),RKT(K))
      AK2= (RKVX(K)+AM1/2.)*H
      AL2= (RKVY(K)+AP1/2.)*H
      A1= RKX(K)+AK1/2.
      B1= RKY(K)+AL1/2.
      C1= RKVX(K)+AM1/2.
      D1= RKVY(K)+AP1/2.
      E1= RKT(K)+H/2.
      AM2 = FUNCT1(A1,B1,C1,D1,E1)*H
      AP2 = FUNCT2(A1,B1,C1,D1,E1)*H
      AK3= (RKVX(K)+AM2/2.)*H
      AL3= (RKVY(K)+AP2/2.)*H
      A2= RKX(K)+AK2/2.
      B2= RKY(K)+AP2/2.
      C2= RKVX(K)+AM2/2.
      D2= RKVY(K)+AP2/2.
      E2= RKT(K)+H/2.
      AM3 = FUNCT1(A2,B2,C2,D2,E2)*H
      AP3 = FUNCT2(A2,B2,C2,D2,E2)*H
      AK4= (RKVX(K)+AM3)*H
      AL4= (RKVY(K)+AP3)*H
      A3= RKX(K)+AK3
      B3= RKY(K)+AL3
      C3= RKVX(K)+AM3
      D3= RKVY(K)+AP3
      E3= RKT(K)+H
      AM4 = FUNCT1(A3,B3,C3,D3,E3)*H
      AP4 = FUNCT2(A3,B3,C3,D3,E3)*H
      DELTX = (AK1+2.*AK2+2.*AK3+AK4)/6.
      DELTY = (AL1+2.*AL2+2.*AL3+AL4)/6.
      DELTVX= (AM1+2.*AM2+2.*AM3+AM4)/6.
      DELTVY= (AP1+2.*AP2+2.*AP3+AP4)/6.
```

```
      RKT(K+1)= RKT(K)+H
      RKX(K+1)= RKX(K)+DELTX
      RKY(K+1)= RKY(K)+DELTY
      RKVX(K+1)= RKVX(K)+DELTVX
      RKVY(K+1)= RKVY(K)+DELTVY
      F(K+1)= FUNCT1(RKX(K+1),RKY(K+1),RKVX(K+1),RKVY(K+1),RKT(K+1))
      G(K+1)= FUNCT2(RKX(K+1),RKY(K+1),RKVX(K+1),RKVY(K+1),RKT(K+1))
  100 CONTINUE
C
C     CORRECTION OF THE INTEGRATION
C
      CALL DELTD (F,DELF,DEL2F,DEL3F,DEL4F)
      CALL DELTD (G,DELG,DEL2G,DEL3G,DEL4G)
      RKVX(2)= RKVX(1)+H*(F(1)+DELF/2.-DEL2F/12.+DEL3F/24.-DEL4F/40.)
      RKVY(2)= RKVY(1)+H*(G(1)+DELG/2.-DEL2G/12.+DEL3G/24.-DEL4G/40.)
      RKX(2)= RKX(1)+H*(RKVX(1)+RKVX(2))/2.
      RKY(2)= RKY(1)+H*(RKVY(1)+RKVY(2))/2.
      DO 10 J=1,3
      F(J+1)= FUNCT1(RKX(J+1),RKY(J+1),RKVX(J+1),RKVY(J+1),RKT(J+1))
      G(J+1)= FUNCT2(RKX(J+1),RKY(J+1),RKVX(J+1),RKVY(J+1),RKT(J+1))
      RKVX(J+2)= RKVX(J)+(F(J+2)+4.*F(J+1)+F(J))*H/3.
      RKVY(J+2)= RKVY(J)+(G(J+2)+4.*G(J+1)+G(J))*H/3.
      FC= FUNCT1(RKX(J+2),RKY(J+2),RKVX(J+2),RKVY(J+2),RKT(J+2))
      GC= FUNCT2(RKX(J+2),RKY(J+2),RKVX(J+2),RKVY(J+2),RKT(J+2))
      RKVX(J+2)= RKVX(J+2)+(FC-F(J+2))*H/3.
      RKVY(J+2)= RKVY(J+2)+(GC-G(J+2))*H/3.
      RKX(J+2)= RKX(J+1)+H*(RKVX(J+2)+RKVX(J+1))/2.
      RKY(J+2)= RKY(J+1)+H*(RKVY(J+2)+RKVY(J+1))/2.
      F(J+2)= FC
   10 G(J+2)= GC
      WRITE(3,20)(RKT(I),RKX(I),RKY(I),RKVX(I),RKVY(I),I=1,5)
   20 FORMAT(F5.1,E10.3,3F9.4)
C
C     FORWARD INTEGRATION
C
      VX(N+1)= RKVX(4)+ H*(2.*F(5)+(F(3)-2.*F(2)+F(1))/3.+F(5)-F(2)
     1+3.*F(3)-3.*F(4))
      VY(N+1)= RKVY(4)+ H*(2.*G(5)+(G(3)-2.*G(2)+G(1))/3.+G(5)-G(2)
     1+3.*G(3)-3.*G(4))
      X(N+1)= RKX(4)+H*(2.*RKVX(5)+(VX(N+1)-2.*RKVX(5)+RKVX(4))/3.)
      Y(N+1)= RKY(4)+H*(2.*RKVY(5)+(VY(N+1)-2.*RKVY(5)+RKVY(4))/3.)
      T(N+1)= T(N)+DELT
      FL= FUNCT1(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
      GL= FUNCT2(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
      VX(N+1)= RKVX(4)+H*(F(4)+4.*F(5)+FL)/3.
      VY(N+1)= RKVY(4)+H*(G(4)+4.*G(5)+GL)/3.
      X(N+1)= RKX(4)+H*(RKVX(4)+4.*RKVX(5)+VX(N+1))/3.
      Y(N+1)= RKY(4)+H*(RKVY(4)+4.*RKVY(5)+VY(N+1))/3.
      FL= FUNCT1(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
      GL= FUNCT2(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
      RETURN
      END
```

```
      SUBROUTINE DELTD(A,B,E,D,DEL4)
      REAL MACHA,MACHGA
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),J
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      DIMENSION A(5),DEL(4),DEL2(3),DEL3(2)
      DO 1 I=1,4
    1 DEL(I)= A(I+1)-A(I)
      DO 2 K=1,3
    2 DEL2(K)= DEL(K+1)-DEL(K)
      DO 3 JK=1,2
    3 DEL3(JK)= DEL2(JK+1)-DEL2(JK)
      B= DEL(1)
      E= DEL2(1)
      D= DEL3(1)
      DEL4= DEL3(2)-DEL3(1)
      RETURN
      END
```

```
      FUNCTION FUNCTI(AA,BA,CA,DA,EA)
      REAL MACHA,MACHGA
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),J
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      PGO= 100.-GCR*EA
      IF(PGO.LE.0.)GO TO 100
      CD= (1.049E-04)+(7.062E-03)*PGO-(5.830E-05)*PGO**2+(2.398E-06)
     1*PGO**3-(3.578E-08)*PGO**4+(1.987E-10)*PGO**5
      GO TO 101
  100 PGO= 0.
      CD= 0.
  101 VHP= CA**2/64.4
      VHGC= DA**2/64.4
      VHR= (CA-DA*AU/AREAP)**2/64.4
      IF(JFIRST.GE.4)VHR=(CA-DA*AD/AREAP)**2/64.4
      PP= 91.75-VHP*(2.-VHR/VHP)+VHR*(1.-(AREAP/AG/CD)**2)
      IF(DA.LT.0.)PP=91.75-VHP*(10.34*(ABS(AU*DA/AREAP/CA)-.18)**3+.18**
     13*10.34+1.)+VHR*(1.-(AREAP/AG/CD)**2)
      PT= PP+VHP*(4.*DA*AU/CA/AREAP-(2.-(AREAP/AD)**2)*(AU*DA/AREAP/CA)
     1**2)-VHGC*(AU/AD)**2-13.5
      IF(JFIRST.GE.4)PT= PP+VHP*(4.*DA*AD/CA/AREAP-(2.-(AREAP/AD)**2)
     1*(AD*DA/AREAP/CA)**2)-VHGC-13.5
      PVAPOR= .35-2.30769*PATM
      IF(PT.GT.PVAPOR)GO TO 400
      PT= PVAPOR
      PP= PT-VHP*(4.*DA*AU/CA/AREAP-(2.-(AREAP/AD)**2)*(AU*DA/AREAP/CA)
     1**2)+VHGC*(AU/AD)**2+13.5
      IF(JFIRST.GE.4)PP= PT-VHP*(4.*DA*AD/CA/AREAP-(2.-(AREAP/AD)**2)
     1*(AD*DA/AREAP/CA)**2)+VHGC+13.5
      JFIRST= 100
  400 P3(J)= PT
      FUNCT1= 32.2/PL*(PP-VHP*(TLOSS-1.+FP*PL/13.5)+313.25)
      RETURN
      END
```

```
      FUNCTION FUNCT2(AB,BB,CB,DB,EB)
      REAL MACHA,MACHGA
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),J
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      PT= P3(J)
      VHP= CB**2/64.4
      VHGC= DB**2/64.4
      VHR= (CB-DB*AU/AREAP)**2/64.4
      IF(JFIRST.GE.4)VHR= (CB-DB*AD/AREAP)**2/64.4
      PP= 91.75-VHP*(2.-VHR/VHP)*VHR*(1.-(AREAP/AG/CD)**2)
      IF(DB.LT.0.)PP=91.75-VHP*(10.34*(ABS(AU*DB/AREAP/CB)-.18)**3+.18**
     13*10.34+1.)+VHR*(1.-(AREAP/AG/CD)**2)
      PT= PP+VHP*(4.*DB*AU/CB/AREAP-(2.-(AREAP/AD)**2)*(AU*DB/AREAP/CB)
     1**2)-VHGC*(AU/AD)**2-13.5
      IF(JFIRST.GE.4)PT= PP+VHP*(4.*DB*AD/CB/AREAP-(2.-(AREAP/AD)**2)
     1*(AD*DB/AREAP/CB)**2)-VHGC-13.5
      PVAPOR= .35-2.30769*PATM
      IF(PT.GT.PVAPOR)GO TO 400
      PT= PVAPOR
      PP= PT-VHP*(4.*DB*AU/CB/AREAP-(2.-(AREAP/AD)**2)*(AU*DB/AREAP/CB)
     1**2)+VHGC*(AU/AD)**2+13.5
      IF(JFIRST.GE.4)PP= PT-VHP*(4.*DB*AD/CB/AREAP-(2.-(AREAP/AD)**2)
     1*(AD*DB/AREAP/CB)**2)+VHGC+13.5
      JFIRST= 100
  400 P3(J)= PT
      IF(DB.LT.0.)GO TO 600
      IF(JFIRST.GE.4)GO TO 500
      FUNCT2= 32.2/(HCOL-BB+26.25*AU/AD)*(PGC-2.30769*PATM-PT+HCOL
     1-BB+26.25-VHGC*((AU/AD)**2+1.+EK*(AU/AD)**2))
      RETURN
  500 FUNCT2= 32.2*AD/AU/(26.25+HCOL-BB)*(PGC-2.30769*PATM+26.25+HCOL
     1-BB-VHGC*(HCOL+26.25-BB)*FP/2.34*(AU/AD)**2-PT)
      RETURN
  600 FUNCT2= 32.2/(HCOL-BB+(AU/AD)*26.25)*(PGC-2.30769*PATM-PT+HCOL
     1-BB+26.25-VHGC*(.5*(AU/AD)**2-1.))
      RETURN
      END
```

```
      SUBROUTINE DE1(X,VX,U,DELT,L)
      REAL MACHA,MACHGA
      DIMENSION X(50),VX(50),RX(5),RVX(5),RT(5),RF(5),F(5),U(50)
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),NUT
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      N= NUT-1
      RX(1)= X(N)
      RVX(1)= VX(N)
      RT(1)= T(N)
      H= DELT/5.
      RF(1)= FUNCT3(RX(1),RVX(1),RT(1))
      DO 100 K=1,4
      AK1= FUNCT3(RX(K),RVX(K),RT(K))*H
      A1= RX(K)+RVX(K)*H/2.+AK1*H/8.
      B1= RVX(K)+AK1/2.
      C1= RT(K)+H/2.
      AK2= FUNCT3(A1,B1,C1)*H
      B2= RVX(K)+AK2/2.
      AK3= FUNCT3(A1,B2,C1)*H
      A3= RX(K)+RVX(K)*H+AK3*H/2.
      B3= RVX(K)+AK3
      C3= RT(K)+H
      AK4= FUNCT3(A3,B3,C3)*H
      DELTX= H*(RVX(K)+(AK1+AK2+AK3)/6.)
      DELTVX= (AK1+2.*AK2+2.*AK3+AK4)/6.
      RX(K+1)= RX(K)+DELTX
      RVX(K+1)= RVX(K)+DELTVX
      RT(K+1)= RT(K)+H
  100 RF(K+1)= FUNCT3(RX(K+1),RVX(K+1),RT(K+1))
      CALL DELTD(RVX,DELF,DEL2F,DEL3F,DEL4F)
      RX(2)= RX(1)+H*(RVX(1)+DELF/2.-DEL2F/12.+DEL3F/24.-DEL4F/40.)
      CALL DELTD(RF,DELF,DEL2F,DEL3F,DEL4F)
      RVX(2)= RVX(1)+H*(RF(1)+DELF/2.-DEL2F/12.+DEL3F/24.-DEL4F/40.)
      DO 10 J=1,3
      RF(J+1)= FUNCT3(RX(J+1),RVX(J+1),RT(J+1))
      RVX(J+2)= (RF(J+2)+4.*RF(J+1)+RF(J))*H/3.+RVX(J)
   10 RX(J+2)= (RVX(J+2)+4.*RVX(J+1)+RVX(J))*H/3.+RX(J)
      WRITE(3,20)(RT(I),RX(I),RVX(I),I=1,5)
   20 FORMAT(F5.1,E10.3,F9.4)
      RF(5)= FUNCT3(RX(5),RVX(5),RT(5))
      VX(N+1)= RVX(4)+H*(2.*RF(5)+(RF(3)-2.*RF(2)+RF(1))/3.+
     1RF(5)-3.*RF(4)+3.*RF(3)-RF(2))
      X(N+1)= RX(4)+H*(2.*RVX(5)+(RVX(3)-2.*RVX(2)+RVX(1))/3.+
     1RVX(5)-3.*RVX(4)+3.*RVX(3)-RVX(2))
      T(N+1)= T(N)+DELT
      F= FUNCT3(X(N+1),VX(N+1),T(N+1))
      RETURN
      END
```

```
      FUNCTION FUNCT3(AC,BC,DC)
      REAL MACHA,MACHGA
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),J
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      JN= J-1
      PGO= 100.-GCR*DC
      IF(PGO.LE.0.)GO TO 100
      CD= (1.049E-04)+(7.062E-03)*PGO-(5.830E-05)*PGO**2+(2.398E-06)
     1*PGO**3-(3.578E-08)*PGO**4+(1.987E-10)*PGO**5
      GO TO 101
  100 PGO= 0.
      CD= 0.
  101 QRTST= AG*CD*SQRT(64.4*(91.75+PGC-2.30769*PATM))
      GATEZ= 7073.25+13.5*PGO/100.
      IF(WS.GT.GATEZ)QRTST= AG*CD*SQRT(64.4*(91.75-PP+PGC-2.30769*PATM))
      DT= (DC-T(JN))
      IF(DT.LE.0.)GO TO 1
      DQRDT= (QR-QRTST)/DT
      WS= 7087.8-(AC*AREAP-(2.*QRTST-DQRDT*DT)*DT/2.)/496.9
      IF(WS.GE.7087.8)WS= 7087.8
      IF(WS.LE.7073.25)WS= 7073.25-(AC*AREAP-(2.*QRTST-DQRDT*DT)*DT/2.
     1-7229.9)/143.14
    1 VHP= BC**2/64.4
      IF(WS.LE.7073.25)PL= 1.14*WS-7652.08
      DWS= 313.25
      IF(WS.LE.7073.25)DWS= WS-6760.
      PP= 2.30769*(ABSPGC-PATM)
      IF(JFIRST.EQ.7.AND.DT.LE.(1.E-30))PPFRST= VHP*(TLOSS-1.+FP*PL/
     113.5)-DWS-ENRTAP(JN)
      IF(WS.GE.7073.25)PP= (WS-7073.25)*PPFRST/14.55+2.30769*(ABSPGC-
     1PATM)
      FUNCT3= 32.2/PL*(PP-VHP*(TLOSS-1.+FP*PL/13.5)+DWS)
      WRITE(3,2)WS,DQRDT,CD,FUNCT3,QRTST,DT
    2 FORMAT(2F8.2,F8.4,2E11.4,F8.4)
      RETURN
      END
```

```
      SUBROUTINE AMACH(CINC,MINC,FRICT,AVENT,DELT,PGCINC,WTAIR,CONST,
     1CKA)
      REAL M1R,M1I,MACHIN,MACHGC,MACH,MINC,MACSAV
      REAL MACHA,MACHGA
      COMMON CD,DELTVX,DELTVY,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,
     1PP,P3(50),J
     2,PL,FP,TLOSS,AU,AD,AREAP,AG,EK
     3,GCR,PGO,JFIRST,
     4WTFLA(50),MACHA(50),MACHGA(50)
     5,AVOL,PIN,C
     6,T(50),JCK
     7,ENRTAP(50)
      EQ(MACH)= (1.-MACH**2)/(1.4*MACH**2)+.857*ALOG((1.2*MACH**2)/       *
     1(1.+.2*MACH**2))
      JN= J-1
      MACHIN= MACHA(J-1)
      MACHGC= MACHGA(J-1)
      IF(MACHIN.LE.(1.E-30))MACHIN=.0001
      M1I=2.*MACHIN
      JCK= 1
      DM1I= MACHIN/10.
C
C     COMPUTATION OF AIR VOLUME IN GATE CHAMBER AND PENSTOCK
C
      RC= 1./(1.2)**3.5                                                    *
      AVOL= 1064647.-AU*WS                                                 *
      AVOLU= 1064647.-AU*7113.                                             *
      IF(WS.LE.7113.) AVOL= AVOLU+(7113.-WS)*AD                            *
      IF(WS.LE.7087.8) AVOL= AVOLU+25.2*AD+(7087.8-WS)*496.9               *
      IF(WS.LE.7073.25) AVOL= AVOLU+25.2*AD+7230.+(7073.25-WS)*AREAP       *
C
C     COMPUTATION OF THE PRESSURE RATIO,THE COMPRESSIBLE DISCHARGE
C     COEFFICIENT, THE REAL MACH NUMBER AT 1,AND THE AIR FLOW RATE
C     GIVEN THE IDEAL MACH NUMBER AT THE BEGINNING OF THE DUCT REGION
C
      NLUP= 1
      PGCSAV= ABSPGC
      DO 60 NDO=1,100
      R= 1./(1.+.2*M1I**2)**3.5
      IF((R/RC).LE.1.)GO TO 21                                             *
      C= 1.-.5*(1.-.28*(1./R-1.)/(1./RC-1.))
      GO TO 22                                                             *
   21 C= 1.-.5*(.72-.32*(1.-(R/RC)**2))
   22 RADICL= 1.+.8*C**2*(M1I**2+.2*M1I**4)
      ROOT= SQRT(RADICL)
      M1R= SQRT((-1.+ROOT)/.4)
      MACHIN= M1R
      ENT= (C*M1I/M1R)**7.
      IF(M1I.LE.0.001)ENT= 1.
      PIN= ENT*PATM
      WTFLA(J)= 5.925*AVENT*PATM*ENT*M1R/(1.+.2*M1R**2)**3                 *
C
C     COMPUTATION OF MACH NO. AT OUTLET OF AIR DUCT
C
  216 IF(MACHIN .GT..0005) GO TO 1116
      MACHGC = MACHIN
      GO TO 97
```

```
1116 EQRH= EQ(MACHIN)
     EQLH= EQ(MACHGC)
     CK = EQRH - EQLH - FRICT
     IF(CK) 403,97,401
 401 MACHGC = MACHGC - .01
     IF (MACHGC) 404,404,405
 403 MACHGC = MACHGC + .01
     IF(MACHGC - 1.)405,280,280
 404 MACHGC = (MACHGC + .01) / 2.
 405 EQLH= EQ(MACHGC)
     CKM = EQRH - EQLH - FRICT
     DO 96 K=1,100
     IF (CK) 407,97,406
 406 IF(CKM) 55,97,409
 407 IF(CKM) 408,97,55
 408 MACHGC = MACHGC + .01
     IF(MACHGC - 1.)410,280,280
 409 MACHGC = MACHGC - .01
     IF (MACHGC) 411,411,410
 411 MACHGC = (MACHGC + .01) / 2.
 410 EQLH= EQ(MACHGC)
     CK = CKM
     CKM = EQRH - EQLH - FRICT
  96 CONTINUE
C
C    COMPUTATION OF MACH OUT BY NEWTONS METHOD
C
  55 CK = CKM
     IF(CK) 106,97,105
 105 MACHGC = MACHGC - .01
     EQLH= EQ(MACHGC)
     CK = EQRH - EQLH - FRICT
 106 DO 95 KK = 1,100
     IF(ABS(CK/EQRH) .LE. MINC) GO TO 97
 155 DCKDM = (1. - MACHGC**2) / (.7*MACHGC**3 + .14*MACHGC**5)
     MACHGC = MACHGC - CK/DCKDM
     IF(MACHGC.LE.0.)GO TO 203
     IF(MACHGC.GT.1.)GO TO 280
     EQLH= EQ(MACHGC)
     CK = EQRH - EQLH - FRICT
  95 CONTINUE
     GO TO 97
C
C    COMPUTATION OF AIR FLOW RATE WITH MACH 1 AT DUCT OUTLET
C
 280 MACHGC= 1.
     MACHIN = 0.
     DO 296 N=1,100
     MACHIN = MACHIN + .05
     EQRH= EQ(MACHIN)
     IF(EQRH-FRICT)262,87,296
 262 MACHIN = MACHIN - .05
     IF(MACHIN.LE.0.)GO TO 203
     EQRH= EQ(MACHIN)
     DO 295 MM=1,100
     IF(ABS(EQRH-FRICT).LE.MINC)GO TO 87
```

```
   81 DEQDM = (1. - MACHIN**2) / (.7*MACHIN**3 + .14*MACHIN**5)
      MACHIN = MACHIN - (EQRH - FRICT)/DEQDM*(-1.)
      EQRH= EQ(MACHIN)
  295 CONTINUE
  296 CONTINUE
   87 M1I= MACHIN+.3
      MACSAV= MACHIN
      DO 2 MOON=1,50
      R= 1./(1.+.2*M1I**2)**3.5
      IF((R/RC).LE.1.)GO TO 11
      C= 1.-.5*(1.-.28*(1./R-1.)/(1./RC-1.))
      GO TO 12
   11 C= 1.-.5*(.72-.32*(1.-(R/RC)**2))
   12 RADICL= 1.+.8*C**2*(M1I**2+.2*M1I**4)
      ROOT= SQRT(RADICL)
      M1R= SQRT((-1.+ROOT)/.4)
      ENT= (C*M1I/M1R)**7.
      PIN= ENT*PATM
      WTFLA(J)= 5.925*AVENT*PATM*ENT*M1R/(1.+.2*M1R**2)**3
      IF(ABS(M1R-MACSAV).LE.MINC)GO TO 97
      M1I= M1I-MINC/2.
      IF(M1R.LE.MACSAV)M1I=M1I+MINC
    2 CONTINUE
C
C     ADIABATIC EXPANSION OF AIR IN THE GATE CHAMBER GIVES THE GATE
C     CHAMBER PRESSURE PGCTST
C
   97 PGCTST= (CONST*(2.*WTAIR+(WTFLA(JN)+WTFLA(J))*DELT)**1.4)/
     1(2.*AVOL)**1.4
      IF(JCK.EQ.3)PGCTST= CONST*((WTAIR+WTFLA(J)*DELT)/AVOL)**1.4
C
C     COMPUTATION OF PRESSURE AT END OF DUCT FLOW SECTION
C
  146 PGCTRL= PIN*MACHIN/MACHGC*SQRT(((1.+.2*MACHGC)/
     1(1.+.2*MACHIN))**6)
C
      WRITE(3,1)R,C,M1R,M1I,ENT,WTFLA(J),MACHIN,MACHGC
      WRITE(3,4)PGCTST,PGCTRL,PIN,WTAIR,WTFLA(JN),AVOL,CONST
    1 FORMAT(8F9.4)
    4 FORMAT(3F9.4,E10.3,F9.4,E10.3,F9.4)
      CKA = PGCTRL - PGCTST
      ABSPGC = (PGCTRL + PGCTST) / 2.
      PGC = 1.153845 * (PGCTRL + PGCTST)
      IF(ABS(PGCTRL-PGCTST).LE.PGCINC)GO TO 281
      IF(NDO.EQ.1)GO TO 50
      IF(NLUP.EQ.2)GO TO 50
      DM1I= CKA*DM1I/(CKASAV-CKA)
   50 IF(NDO.EQ.1.AND.CKA.LE.0.)DM1I= (-1.)*M1I/2.
      M1I= M1I+DM1I
      IF(M1I.LE.(1.E-30))GO TO 203
      NLUP= 1
      CKASAV= CKA
      GO TO 60
C
C     COMPUTATION WITH NEGATIVE MACH NUMBERS AT ENTRANCE OF DUCT SECTION
C
  203 JCK= 3
```

```
      RNLUP= NLUP
      M1I= MINC/RNLUP
      NLUP= NLUP+1
      DM1I= M1I
   60 CONTINUE
  281 MACHA(J)= M1R
      MACHGA(J)= MACHGC
      RETURN
      END
```

PROGRAM OUTPUT

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE
11.26 PSI

SPECIFIC WEIGHT OF AIR
.0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

TIME (SEC)	Q GATE CHAMBER (CFS)	Q RES (CFS)	Q PENSTOCK (CFS)	WS ELEV	GATE CHAMBER PRESS (PSIA)	INLET AIR VEL (FT/SEC)	OUTLET AIR VEL (FT/SEC)
.0	.0	2544.4	2544.4	7162.65	11.260	.0	.0
1.0	3.5	2540.5	2543.9	7162.64	11.260	.3	.3
2.0	12.9	2530.2	2543.2	7162.59	11.262	1.6	1.6
3.0	26.0	2516.2	2542.3	7162.46	11.260	2.4	3.0
4.0	39.4	2501.9	2541.3	7162.23	11.260	3.2	4.8
5.0	50.1	2490.3	2540.4	7161.93	11.259	5.5	6.0
6.0	56.3	2483.2	2539.5	7161.57	11.259	6.9	6.9
7.0	57.3	2481.3	2536.7	7161.19	11.259	5.9	6.8
8.0	54.2	2483.7	2537.9	7160.81	11.259	5.9	6.6
9.0	48.5	2488.6	2537.1	7160.46	11.259	4.4	5.7
10.0	42.4	2493.8	2536.2	7160.16	11.260	1.9	5.2
11.0	37.8	2497.6	2535.3	7159.89	11.260	4.4	4.4
12.0	35.8	2498.6	2534.4	7159.64	11.260	4.4	4.4
13.0	37.0	2496.3	2533.3	7159.40	11.260	3.6	4.3
14.0	40.9	2491.3	2532.2	7159.14	11.259	4.7	5.0
15.0	46.7	2484.3	2531.0	7158.84	11.259	5.1	5.5
16.0	53.1	2476.7	2529.8	7158.51	11.259	5.1	6.5
17.0	59.1	2469.4	2528.5	7158.13	11.259	7.1	7.0
18.0	64.0	2463.2	2527.2	7157.72	11.259	7.4	7.8
19.0	67.7	2458.1	2525.8	7157.27	11.259	7.1	8.0
20.0	70.4	2453.9	2524.3	7156.81	11.258	7.8	8.5
21.0	72.7	2450.0	2522.7	7156.33	11.259	7.4	8.6
22.0	75.2	2445.9	2521.1	7155.83	11.258	8.6	9.1
23.0	78.3	2441.0	2519.3	7155.31	11.258	8.6	9.3
24.0	82.5	2434.9	2517.5	7154.77	11.258	9.1	9.9
25.0	87.8	2427.5	2515.4	7154.20	11.258	9.5	10.5
26.0	94.2	2418.9	2513.2	7153.59	11.256	11.7	11.3
27.0	101.5	2409.3	2510.8	7152.93	11.256	12.2	12.2
28.0	109.7	2398.6	2508.3	7152.22	11.255	13.3	13.1
29.0	118.6	2387.0	2505.6	7151.45	11.255	14.4	14.2
30.0	128.2	2374.4	2502.6	7150.62	11.254	15.0	15.4
31.0	138.7	2360.7	2499.4	7149.72	11.253	16.2	16.6
32.0	150.1	2345.8	2495.9	7148.75	11.252	17.5	18.0
33.0	162.6	2329.5	2492.1	7147.70	11.251	19.0	19.4
34.0	176.3	2311.6	2487.9	7146.56	11.249	20.5	21.1
35.0	191.5	2291.9	2483.4	7145.32	11.247	22.3	22.9
36.0	208.2	2270.3	2478.4	7143.98	11.245	24.2	24.9
37.0	226.5	2246.5	2473.0	7142.52	11.242	26.3	27.0
38.0	246.7	2220.3	2467.0	7140.93	11.238	28.7	29.5
39.0	268.9	2191.6	2460.5	7139.19	11.234	31.2	32.1
40.0	293.2	2160.1	2453.3	7137.30	11.230	34.1	35.0

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE
11.26 PSI

SPECIFIC WEIGHT OF AIR
.0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

TIME (SEC)	PRESS AT 3 (FT)	PENSTOCK PRESS (FT)	GATE OPENING (O/O)	COEFF DISCH.	INERTIAL TERMS GATE	PENSTOCK
.0	75.90	89.40	100.0	.9303	.0000	-.0000
1.0	75.70	89.17	98.3	.8924	-.1836	.0720
2.0	75.51	88.91	96.7	.8570	-.3220	.0874
3.0	75.32	88.62	95.0	.8240	-.3717	.0950
4.0	75.12	88.32	93.3	.7932	-.3374	.0961
5.0	74.91	88.03	91.7	.7644	-.2333	.0931
6.0	74.68	87.75	90.0	.7374	-.0960	.0881
7.0	74.43	87.49	88.3	.7120	.0335	.0837
8.0	74.15	87.24	86.7	.6882	.1268	.0819
9.0	73.85	86.98	85.0	.6657	.1656	.0833
10.0	73.54	86.72	83.3	.6445	.1495	.0879
11.0	73.21	86.43	81.7	.6244	.0912	.0948
12.0	72.89	86.11	80.0	.6053	.0101	.1027
13.0	72.56	85.78	78.3	.5870	-.0706	.1105
14.0	72.23	85.42	76.7	.5696	-.1330	.1175
15.0	71.90	85.04	75.0	.5529	-.1658	.1234
16.0	71.55	84.65	73.3	.5368	-.1677	.1286
17.0	71.19	84.24	71.7	.5212	-.1446	.1337
18.0	70.80	83.81	70.0	.5062	-.1121	.1394
19.0	70.38	83.37	68.3	.4915	-.0820	.1463
20.0	69.93	82.90	66.7	.4772	-.0624	.1546
21.0	69.45	82.40	65.0	.4632	-.0598	.1643
22.0	68.93	81.87	63.3	.4495	-.0704	.1754
23.0	68.39	81.30	61.7	.4360	-.0936	.1876
24.0	67.81	80.69	60.0	.4227	-.1215	.2009
25.0	67.20	80.04	58.3	.4096	-.1497	.2154
26.0	66.54	79.34	56.7	.3966	-.1727	.2313
27.0	65.84	78.59	55.0	.3837	-.1947	.2490
28.0	65.09	77.78	53.3	.3709	-.2126	.2686
29.0	64.28	76.90	51.7	.3583	-.2293	.2906
30.0	63.40	75.95	50.0	.3457	-.2478	.3151
31.0	62.45	74.93	48.3	.3331	-.2669	.3423
32.0	61.41	73.81	46.7	.3207	-.2889	.3725
33.0	60.28	72.59	45.0	.3083	-.3141	.4059
34.0	59.05	71.27	43.3	.2960	-.3422	.4429
35.0	57.71	69.83	41.7	.2837	-.3726	.4839
36.0	56.25	68.25	40.0	.2715	-.4049	.5293
37.0	54.65	66.53	38.3	.2594	-.4394	.5796
38.0	52.90	64.64	36.7	.2474	-.4753	.6355
39.0	50.97	62.58	35.0	.2354	-.5134	.6975
40.0	48.87	60.32	33.3	.2235	-.5525	.7664

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE 11.26 PSI

SPECIFIC WEIGHT OF AIR .0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

TIME (SEC)	MACH NO. AT INLET	MACH NO. AT OUTLET	SPECIFIC WEIGHT OF AIR LB/CU FT	SPECIFIC VOLUME OF AIR CU FT/LB	AIR FLOW RATE LBM/SEC	ACCURACY OF PRESS CALC. (PSI)
.0	.0000	.0000	.0596	16.78	.00	.0000
1.0	.0003	.0003	.0596	16.78	.14	-.0000
2.0	.0014	.0014	.0596	16.78	.79	.0009
3.0	.0027	.0027	.0596	16.78	1.51	-.0001
4.0	.0044	.0044	.0596	16.78	2.40	-.0006
5.0	.0054	.0054	.0596	16.78	2.97	-.0001
6.0	.0062	.0062	.0596	16.78	3.42	.0002
7.0	.0062	.0062	.0596	16.78	3.40	-.0005
8.0	.0060	.0060	.0596	16.78	3.28	-.0003
9.0	.0052	.0052	.0596	16.78	2.86	-.0006
10.0	.0047	.0047	.0596	16.78	2.56	-.0010
11.0	.0040	.0040	.0596	16.78	2.19	.0008
12.0	.0039	.0039	.0596	16.78	2.17	-.0009
13.0	.0039	.0039	.0596	16.78	2.14	-.0002
14.0	.0045	.0045	.0596	16.78	2.48	.0000
15.0	.0050	.0050	.0596	16.78	2.73	.0001
16.0	.0058	.0058	.0596	16.78	3.22	.0001
17.0	.0063	.0063	.0596	16.78	3.47	.0002
18.0	.0070	.0070	.0596	16.78	3.88	.0007
19.0	.0073	.0073	.0596	16.78	3.99	-.0006
20.0	.0077	.0077	.0596	16.78	4.24	.0004
21.0	.0078	.0078	.0596	16.78	4.30	-.0009
22.0	.0082	.0082	.0596	16.78	4.50	-.0002
23.0	.0084	.0084	.0596	16.78	4.64	-.0005
24.0	.0090	.0090	.0596	16.78	4.93	.0006
25.0	.0095	.0095	.0596	16.78	5.21	.0008
26.0	.0102	.0102	.0596	16.78	5.62	.0008
27.0	.0110	.0110	.0596	16.78	6.04	.0004
28.0	.0119	.0119	.0596	16.78	6.53	.0007
29.0	.0128	.0128	.0596	16.78	7.05	.0009
30.0	.0139	.0139	.0596	16.78	7.64	.0001
31.0	.0150	.0150	.0596	16.79	8.23	.0001
32.0	.0163	.0163	.0596	16.79	8.94	.0002
33.0	.0175	.0176	.0596	16.79	9.65	.0002
34.0	.0191	.0191	.0596	16.79	10.49	.0003
35.0	.0207	.0207	.0596	16.79	11.36	.0004
36.0	.0225	.0225	.0595	16.79	12.37	-.0003
37.0	.0244	.0244	.0595	16.80	13.42	-.0003
38.0	.0266	.0267	.0595	16.80	14.64	-.0003
39.0	.0290	.0290	.0595	16.81	15.91	-.0003
40.0	.0316	.0317	.0595	16.81	17.36	-.0004

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE 11.26 PSI

SPECIFIC WEIGHT OF AIR .0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

TIME (SEC)	Q GATE CHAMBER (CFS)	Q RES (CFS)	Q PENSTOCK (CFS)	WS ELEV	GATE CHAMBER PRESS (PSIA)	INLET AIR VEL (FT/SEC)	OUTLET AIR VEL (FT/SEC)
40.0	293.2	2160.1	2453.3	7137.30	11.230	34.1	35.0
41.0	320.0	2125.4	2445.4	7135.24	11.224	37.2	38.2
42.0	349.3	2087.4	2436.7	7132.99	11.217	40.6	41.7
43.0	381.6	2045.6	2427.1	7130.53	11.209	44.3	45.4
44.0	416.9	1999.6	2416.5	7127.85	11.199	48.3	49.6
45.0	455.7	1949.1	2404.8	7124.91	11.187	52.7	54.2
46.0	498.4	1893.4	2391.8	7121.71	11.174	57.6	59.1
47.0	545.3	1832.1	2377.3	7118.20	11.157	62.8	64.6
48.0	596.9	1764.3	2361.3	7114.36	11.138	68.6	70.5
48.3	614.5	1741.2	2355.7	7113.00	11.130	70.6	72.6
49.0	628.2	1713.2	2341.3	7104.08	11.119	73.6	75.7
50.0	610.1	1695.6	2305.6	7090.80	11.125	72.1	74.1
50.2	605.4	1690.9	2296.4	7087.79	11.121	73.1	75.2
51.0	.0	1603.1	2280.7	7086.67	11.068	86.1	88.8
52.0	.0	1434.8	2272.2	7082.46	10.006	232.1	249.8
53.0	.0	1299.1	2252.6	7077.63	9.695	263.6	287.8
54.0	.0	1167.3	2237.2	7071.39	9.565	276.3	303.6
55.0	.0	979.0	2198.4	7054.59	9.533	279.3	307.4
56.0	.0	788.7	2136.9	7038.35	9.561	276.6	304.0
57.0	.0	596.6	2073.9	7022.53	9.604	272.5	298.8
58.0	.0	402.0	2010.3	7007.10	9.654	267.6	292.7
59.0	.0	204.0	1945.7	6992.05	9.707	262.4	286.4
60.0	.0	.0	1879.9	6977.37	9.760	257.2	280.0
61.0	.0	.0	1818.1	6965.17	9.928	240.2	259.5
62.0	.0	.0	1762.9	6952.66	10.021	230.5	248.0
63.0	.0	.0	1706.9	6940.54	10.101	222.0	238.0
64.0	.0	.0	1650.8	6928.81	10.174	214.2	228.9
65.0	.0	.0	1594.7	6917.47	10.240	206.8	220.4
66.0	.0	.0	1538.5	6906.53	10.302	199.8	212.4
67.0	.0	.0	1482.3	6895.97	10.361	192.9	204.6
68.0	.0	.0	1426.0	6885.81	10.418	186.2	197.0
69.0	.0	.0	1369.7	6876.05	10.473	179.5	189.5
70.0	.0	.0	1313.5	6866.67	10.527	172.8	182.0
71.0	.0	.0	1257.2	6857.69	10.579	166.2	174.6
72.0	.0	.0	1200.9	6849.10	10.630	159.5	167.3
73.0	.0	.0	1144.7	6840.91	10.679	152.7	159.9
74.0	.0	.0	1088.4	6833.11	10.727	145.9	152.5
75.0	.0	.0	1032.2	6825.70	10.774	139.1	145.1
76.0	.0	.0	976.0	6818.68	10.818	132.3	137.8
77.0	.0	.0	919.7	6812.06	10.862	125.3	130.3
78.0	.0	.0	863.5	6805.83	10.906	118.0	123.1

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE
11.26 PSI

SPECIFIC WEIGHT OF AIR
.0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

TIME (SEC)	PRESS AT 3 (FT)	PENSTOCK PRESS (FT)	GATE OPENING (O/O)	COEFF DISCH.	INERTIAL GATE	TERMS PENSTOCK
40.0	48.87	60.32	33.3	.2435	-.5525	.7664
41.0	46.55	57.83	31.7	.2118	-.5936	.8429
42.0	44.00	55.10	30.0	.2001	-.6353	.9278
43.0	41.19	52.11	28.3	.1885	-.6780	1.0219
44.0	38.10	48.81	26.7	.1770	-.7201	1.1260
45.0	34.68	45.17	25.0	.1656	-.7609	1.2405
46.0	30.91	41.17	23.3	.1544	-.7973	1.3645
47.0	26.74	36.76	21.7	.1432	-.8248	1.4949
48.0	22.13	31.90	20.0	.1321	-.8320	1.6224
48.3	20.41	30.10	19.4	.1284	-.9085	1.7772
49.0	15.30	24.93	18.3	.1211	.1898	2.7469
50.0	3.75	13.55	16.7	.1102	.3230	3.8500
50.2	.66	10.50	16.3	.1077	-.0005	4.2180
51.0	-.44	9.29	15.0	.0993	.0000	.9550
52.0	-2.89	3.84	13.3	.0885	.0000	3.9810
53.0	-3.61	-.36	11.7	.0777	.0000	2.6420
54.0	-3.91	-3.91	10.0	.0670	.0000	3.5680
55.0	-3.98	-3.98	8.3	.0561	.0000	10.2240
56.0	-3.92	-3.92	6.7	.0452	.0000	9.8138
57.0	-3.82	-3.82	5.0	.0342	.0000	9.0286
58.0	-3.71	-3.71	3.3	.0231	.0000	8.1156
59.0	-3.58	-3.58	1.7	.0117	.0000	7.0497
60.0	-3.46	-3.46	.0	.0000	.0000	5.8111
61.0	-3.07	-3.07	.0	.0000	.0000	3.8494
62.0	-2.86	-2.86	.0	.0000	.0000	3.8823
63.0	-2.67	-2.67	.0	.0000	.0000	3.7688
64.0	-2.51	-2.51	.0	.0000	.0000	3.6463
65.0	-2.35	-2.35	.0	.0000	.0000	3.5217
66.0	-2.21	-2.21	.0	.0000	.0000	3.3970
67.0	-2.07	-2.07	.0	.0000	.0000	3.2735
68.0	-1.94	-1.94	.0	.0000	.0000	3.1532
69.0	-1.82	-1.82	.0	.0000	.0000	3.0363
70.0	-1.69	-1.69	.0	.0000	.0000	2.9231
71.0	-1.57	-1.57	.0	.0000	.0000	2.8145
72.0	-1.45	-1.45	.0	.0000	.0000	2.7104
73.0	-1.34	-1.34	.0	.0000	.0000	2.6105
74.0	-1.23	-1.23	.0	.0000	.0000	2.5157
75.0	-1.12	-1.12	.0	.0000	.0000	2.4259
76.0	-1.02	-1.02	.0	.0000	.0000	2.3433
77.0	-.92	-.92	.0	.0000	.0000	2.2594
78.0	-.82	-.82	.0	.0000	.0000	2.1794

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE
11.26 PSI

SPECIFIC WEIGHT OF AIR
.0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

TIME (SEC)	MACH NO. AT INLET	MACH NO. AT OUTLET	SPECIFIC WEIGHT OF AIR LB/CU FT	SPECIFIC VOLUME OF AIR CU FT/LB	AIR FLOW RATE LBM/SEC	ACCURACY OF PRESS CALC. (PSI)
40.0	.0316	.0317	.0595	16.81	17.36	-.0004
41.0	.0344	.0345	.0595	16.82	18.90	-.0004
42.0	.0376	.0376	.0594	16.82	20.62	-.0004
43.0	.0410	.0411	.0594	16.83	22.47	-.0004
44.0	.0448	.0448	.0594	16.84	24.52	-.0004
45.0	.0489	.0489	.0593	16.86	26.73	-.0004
46.0	.0534	.0535	.0593	16.87	29.15	-.0004
47.0	.0583	.0584	.0592	16.89	31.78	-.0004
48.0	.0636	.0638	.0591	16.91	34.65	-.0004
48.3	.0655	.0657	.0591	16.92	35.65	-.0002
49.0	.0683	.0685	.0591	16.93	37.13	-.0002
50.0	.0669	.0671	.0591	16.92	36.37	-.0002
50.2	.0679	.0681	.0591	16.93	36.90	.0004
51.0	.0800	.0803	.0589	16.99	43.29	.0004
52.0	.2215	.2294	.0548	18.25	108.48	-.0000
53.0	.2532	.2655	.0536	18.67	120.26	.0001
54.0	.2660	.2806	.0530	18.85	124.73	-.0002
55.0	.2691	.2842	.0529	18.90	125.78	-.0000
56.0	.2664	.2810	.0530	18.86	124.85	.0001
57.0	.2622	.2760	.0532	18.80	123.40	-.0003
58.0	.2572	.2702	.0534	18.73	121.68	.0001
59.0	.2520	.2641	.0536	18.65	119.83	.0001
60.0	.2467	.2580	.0538	18.58	117.95	-.0004
61.0	.2296	.2385	.0545	18.36	111.60	.0001
62.0	.2199	.2277	.0548	18.24	107.87	.0001
63.0	.2114	.2182	.0552	18.13	104.51	-.0000
64.0	.2036	.2097	.0554	18.04	101.37	.0001
65.0	.1964	.2017	.0557	17.96	98.38	.0002
66.0	.1894	.1942	.0559	17.88	95.46	.0001
67.0	.1827	.1869	.0562	17.81	92.58	.0002
68.0	.1760	.1798	.0564	17.74	89.71	.0003
69.0	.1695	.1729	.0566	17.67	86.82	.0002
70.0	.1630	.1660	.0568	17.61	83.91	.0003
71.0	.1565	.1591	.0570	17.54	80.96	.0004
72.0	.1500	.1523	.0572	17.48	77.97	.0004
73.0	.1435	.1455	.0574	17.43	74.93	.0006
74.0	.1369	.1387	.0576	17.37	71.83	.0007
75.0	.1304	.1319	.0577	17.32	68.69	.0008
76.0	.1239	.1251	.0579	17.26	65.52	-.0009
77.0	.1172	.1183	.0581	17.21	62.24	-.0010
78.0	.1108	.1117	.0583	17.17	59.07	.0005

LIST OF SYMBOLS FOR PROGRAM TO COMPUTE FLOW CONDITIONS IN INLET REGION OF AIR VENT

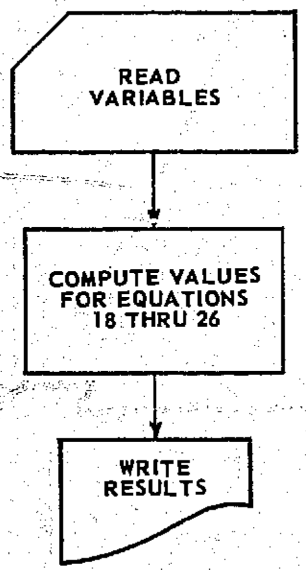
AREA - Area of Air vent (in^2)
CINC - Incompressible discharge coefficient
CCOM - Compressible discharge coefficient
LVEL - Velocity coefficient
EXPENT - Ratio of stagnation pressures
GASCON - Engineering gas constant for air $\left(\frac{ft\ lb_f}{lb_m\ {}^\circ R}\right)$
GRAV - Gravitational constant (ft/sec^2)
K - Isentropic flow constant
MACH21 - Ideal Mach number at end of inlet region
MACH2R - Real Mach number at end of inlet region
MACHSQ - Dummy variable
R - Pressure ratio between atmosphere and end of inlet section
RCRIT - Reciprocal of critical pressure ratio
RC - Dummy variable
RR - Reciprocal of R
T - Temperature (°Rankine)
WTFLO - Mass flow rate of air (lb_m/sec)

COMPUTER REQUIRED

The program was written in FORTRAN II language for use in a GE time-sharing computer. The time required for compilation and execution was about 10 seconds.

FLOW DIAGRAM

FLOW CONDITIONS IN THE INLET REGION OF THE AIR VENT



PROGRAM LISTING

FLOW CONDITIONS IN THE INLET REGION OF THE AIR VENT

```
                   'PRØGRAM TØ CØMPUTE FLØW CØNDITIØNS IN THU'
                      'INLET REGIØN ØF AN AIR VENT PIPE'

      REAL K,MACH2I,MACHSQ,MACH2R
    1 READ,AREA,K,T,GASCØN,GRAV,CINC,PATM
    2 FØRMAT(7F8.4)
      RCRIT= ((K+1.)/2.)**(K/(K-1.))
      PRINT 4
    4 FØRMAT (24X,23H FLØW CØNDITIØNS IN THE /21X,13H INLET REGIØN,
     +16H ØF THE AIR DUCT //1X,34HIDEAL MACH REAL MACHCØMP CØEFFCØMP
     +26H CØEFF ENTRØPY    AIR FLØ ,10H  PRESSURE,/1X,
     +57H  NUMBER      NUMBER  DISCHARGE VELØCITY  EXPØNENT    RATE ,
     +4X,6H RATIØ//)
    6 READ,MACH2I
      CØNKE=  (K-1.)/2.
      R= (1.+CØNKE*MACH2I**2)**(K/(K-1.))
      RC=RCRIT
      CCØM= 1.-(1.-CINC)*(1.-.7*(CINC-.1)-(.27+.1*CINC)*
     +(1.-(RC/R)**2))
      IF(RCRIT-R)3,3
      CCØM= 1.-(1.-CINC)*(1.-.7*(CINC-.1)*(R-1.)/(RC-1.))
    3 MACHSQ=  (-1.+SQRT(1.+2.*(K-1.)*((CCØM*MACH2I)**2
     +*(1.+(K-1.)/2.*MACH2I**2))))/(K-1.)
      MACH2R= SQRT(MACHSQ)
      CUEL= MACHSQ/(CCØM*MACH2I**2)
      EXPENT= (CCØM/CUEL)**(K/(K-1.))
      WTFLØ= PATM*AREA/SQRT(GASCØN*T/(K*GRAV))*EXPENT*
     +MACH2R/(1.+CØNKE*MACHSQ)**((K+1.)/(2.*(K-1.)))
      RR= 1./R
      PRINT 5,MACH2I,MACH2R,CCØM,CUEL,EXPENT,WTFLØ,RR
    5 FØRMAT(1X,5E10.3,E10.4,E10.3)
      GØ TØ 6
     $DATA
99,1.4,520,53.29,32.2,.5,11.26
      1.29,1.3
```

PROGRAM OUTPUT

FLOW CONDITIONS IN THE INLET REGION OF THE AIR VENT

FLØW CØNDITIØNS IN THE
INLET REGIØN ØF THE AIR DUCT

IDEAL MACH NUMBER	REAL MACH NUMBER	CØMP CØEFF DISCHARGE	CØMP CØEFF VELØCITY	ENTRØPY EXPØNENT	AIR FLØ RATE	PRESSURE RATIØ
T = 40 °F						
.100E+00	.501E-01	.501E+00	.502E+00	.995E+00	.2742E+02	.993E+00
.200E+00	.101E+00	.504E+00	.507E+00	.979E+00	.5422E+02	.972E+00
.300E+00	.154E+00	.510E+00	.517E+00	.955E+00	.7984E+02	.939E+00
.400E+00	.210E+00	.518E+00	.530E+00	.923E+00	.1038E+03	.896E+00
.500E+00	.269E+00	.529E+00	.548E+00	.887E+00	.1258E+03	.843E+00
.600E+00	.334E+00	.543E+00	.570E+00	.847E+00	.1456E+03	.784E+00
.700E+00	.405E+00	.561E+00	.596E+00	.807E+00	.1632E+03	.721E+00
.800E+00	.484E+00	.582E+00	.627E+00	.770E+00	.1786E+03	.656E+00
.900E+00	.572E+00	.608E+00	.664E+00	.738E+00	.1921E+03	.591E+00
.100E+01	.671E+00	.640E+00	.704E+00	.715E+00	.2039E+03	.528E+00
.120E+01	.889E+00	.703E+00	.781E+00	.689E+00	.2172E+03	.412E+00
.130E+01	.996E+00	.725E+00	.810E+00	.680E+00	.2167E+03	.361E+00
.140E+01	.110E+01	.743E+00	.833E+00	.672E+00	.2124E+03	.314E+00
.150E+01	.120E+01	.757E+00	.851E+00	.664E+00	.2051E+03	.272E+00

FLØW CØNDITIØNS IN THE
INLET REGIØN ØF THE AIR DUCT

IDEAL MACH NUMBER	REAL MACH NUMBER	CØMP CØEFF DISCHARGE	CØMP CØEFF VELØCITY	ENTRØPY EXPØNENT	AIR FLØ RATE	PRESSURE RATIØ
T = 60 °F						
.100E+00	.501E-01	.501E+00	.502E+00	.995E+00	.2689E+02	.993E+00
.200E+00	.101E+00	.504E+00	.507E+00	.979E+00	.5317E+02	.972E+00
.300E+00	.154E+00	.510E+00	.517E+00	.955E+00	.7829E+02	.939E+00
.400E+00	.210E+00	.518E+00	.530E+00	.923E+00	.1018E+03	.896E+00
.500E+00	.269E+00	.529E+00	.548E+00	.887E+00	.1234E+03	.843E+00
.600E+00	.334E+00	.543E+00	.570E+00	.847E+00	.1428E+03	.784E+00
.700E+00	.405E+00	.561E+00	.596E+00	.807E+00	.1600E+03	.721E+00
.800E+00	.484E+00	.582E+00	.627E+00	.770E+00	.1752E+03	.656E+00
.900E+00	.572E+00	.608E+00	.664E+00	.738E+00	.1884E+03	.591E+00
.100E+01	.671E+00	.640E+00	.704E+00	.715E+00	.1999E+03	.528E+00
.120E+01	.889E+00	.703E+00	.781E+00	.689E+00	.2129E+03	.412E+00
.130E+01	.996E+00	.725E+00	.810E+00	.680E+00	.2125E+03	.361E+00
.140E+01	.110E+01	.743E+00	.833E+00	.672E+00	.2083E+03	.314E+00
.150E+01	.120E+01	.757E+00	.851E+00	.664E+00	.2012E+03	.272E+00

GPO 845-867

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

GPO 835-159

ABSTRACT

A computer program was written to determine the time-magnitude relationships of reduced pressures in the Morrow Point Dam inlet structure. The low pressures are formed during an emergency closure of the intake gates as water in the penstock drains through the turbine. The study was necessary to properly size the air vent system and to investigate the effect of various air vent dimensions on the reduced pressure. Consideration of design parameters, causes for air flow, and flow conditions within the air vent are discussed. The one-dimensional equations of gradually varying unsteady flow are given, and a computer program for their solution is presented in Fortran IV programming language. The program can be used for similar problems.

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Hyd-584
Falvey, Henry T
AIR VENT COMPUTATIONS--MORROW POINT DAM--COLORADO RIVER STORAGE PROJECT. Bur Reclam Lab Rep Hyd-584, Hydraul Br, July 1968. Bureau of Reclamation, Denver, 22 p, 15 fig, 7 tab, 17 ref, append

DESCRIPTORS--/ *vents/ *unsteady flow/ *air demand/ penstocks/ computer programming/ structures/ air/ velocity/ computation/ sound/ reservoirs/ design criteria/ mathematical analysis/ flow control/ adiabatic
IDENTIFIERS--/ Morrow Point Dam, Colo/ Colorado River Storage Proj/ Colorado/ water column separation

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Hyd-584
Falvey, Henry T
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